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Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 3080721 A1 2020/11/14

(21) 3 080 721

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(22) Date de dépôt/Filing Date: 2020/05/13
(41) Mise à la disp. pub./Open to Public Insp.: 2020/11/14
(30) Priorité/Priority: 2019/05/14 (US62/847,489)

(51) Cl.Int./Int.Cl. *F22B 33/00* (2006.01), *E21B 43/24* (2006.01), *F22B 33/18* (2006.01), *F22B 35/08* (2006.01)

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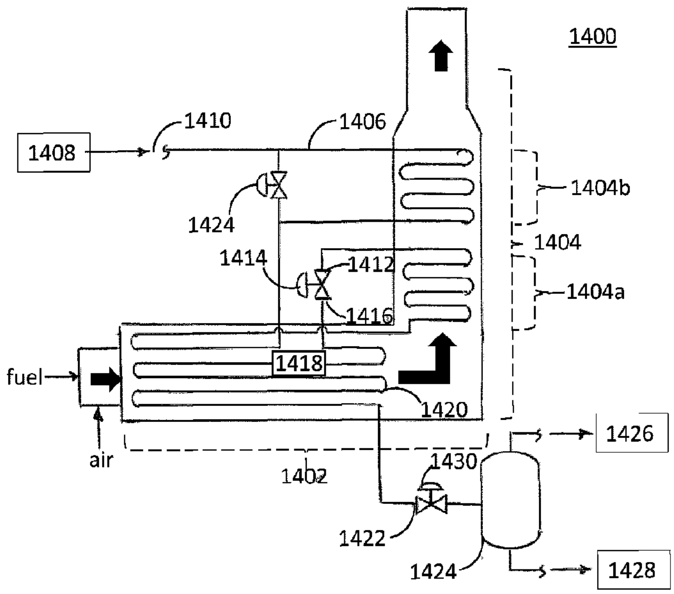
(54) Titre : METHODES ET SYSTEMES POUR GENERATION DE VAPEUR EN DEUX ETAPES
(54) Title: METHODS AND SYSTEMS FOR TWO-STAGE STEAM GENERATION




(57) Abrégé/Abstract:
Methods and systems are disclosed for generating steam for hydrocarbon production. The methods and systems involve a two-stage process. The first stage involves heating a feedwater stream under subcooled conditions so as to remain below the threshold for boiling in the subcooled and saturated nucleate boiling regime. The second stage involves rapidly advancing to a steam quality that surpasses a threshold such that heat transfer occurs in the convective evaporation regime. The methods and systems are particularly suited to producing steam for injection into a hydrocarbon-containing reservoir to facilitate heavy oil and bitumen production.

## ABSTRACT

Methods and systems are disclosed for generating steam for hydrocarbon production. The methods and systems involve a two-stage process. The first stage involves heating a feedwater stream under subcooled conditions so as to remain below the threshold for boiling in the subcooled and saturated nucleate boiling regime. The second stage involves rapidly advancing to a steam quality that surpasses a threshold such that heat transfer occurs in the convective evaporation regime. The methods and systems are particularly suited to producing steam for injection into a hydrocarbon-containing reservoir to facilitate heavy oil and bitumen production.

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# METHODS AND SYSTEMS FOR TWO-STAGE STEAM GENERATION

## TECHNICAL FIELD

**[0001]** The present disclosure generally relates to methods and systems for generating steam for in-situ hydrocarbon recovery processes. In particular, the present disclosure relates to methods and systems that are suitable for generating steam from produced water while attenuating steam generator fouling.

## BACKGROUND

**[0002]** Viscous hydrocarbons can be extracted from some subterranean reservoirs using in-situ recovery processes. Some in-situ recovery processes are thermal processes wherein heat energy is introduced to a reservoir to lower the viscosity of hydrocarbons in situ such that they can be recovered from a production well. In some thermal processes, heat energy is introduced by injecting a heated fluid – typically steam, solvent, or a combination thereof – into the reservoir by way of an injection well that is situated at a well pad. Steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS) are representative thermal-recovery processes that use steam to mobilize hydrocarbons in situ. Solvent-aided processes (SAP) and solvent-driven processes (SDP) are representative thermal-recovery processes that use both steam and solvent to mobilize hydrocarbons in situ.

**[0003]** Regardless of whether a recovery process uses steam alone (*e.g.* SAGD/CSS) or in combination with solvent (*e.g.* SAP/SDP), in situ recovery yields a produced-fluid stream that is likely to contain a mixture of produced water, produced oil, and one or more dissolved or entrained materials derived from the reservoir undergoing the hydrocarbon-recovery process. There are advantages associated with using the produced water as a feedstock for steam generation – namely that the produced water can be recycled during the recovery process thereby increasing system efficiencies and reducing environmental impacts. However, these advantages may be at least partially offset by challenges associated with the recycling process in its conventional form.

**[0004]** In conventional produced water recycling processes, a produced emulsion is recovered from a hydrocarbon reservoir and subjected to coarse oil-water separation to provide a produced water stream. The produced water stream typically contains a variety



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of undesirable dissolved and/or entrained components such as calcium, magnesium, carbonates, silica, and/or silicates. These components (and others) are problematic for steam generation in that they tend to form scale deposits on surfaces within the steam generator (*i.e.* steam generator fouling). Scale deposits are known to reduce the heat transfer coefficient and this insulating effect reduces operational efficiency and requires a higher heated surface temperature to effect available heat transfer potential. Scale deposits are also associated with increased maintenance requirements, more frequent generator shut downs, and/or more frequent boiler tube failures. Accordingly, conventional produced water recycling processes typically employ water treatment steps such as lime softening and/or ion exchange which are designed to decrease the concentration of undesirable dissolved/entrained components to levels that meet or exceed industry standards for steam generation feedwaters. Water treatment steps typically require specialized equipment, increase energy demand, consume materials, create waste, and increase system complexity. Accordingly, methods for water heating, particularly steam generation, that reduce or eliminate the requirement for water treatment after emulsion separation are desirable – especially when such methods attenuate fouling caused by scale deposition.

**[0005]** Steam generator fouling is associated with nucleate boiling which is one of a series of phenomena that may occur as feedwater is converted to steam. Briefly stated, boiling in a steam generator is induced by heat transfer through a super-heated surface, and the mechanism of heat transfer to the feedwater may change as a function of the magnitude of the heat flux and/or the difference in temperature between the super-heated surface and the feedwater, the local fluid velocity, the thermo-physical properties of the fluid, and/or steam quality. In general, heat transfer in a steam generator proceeds from a forced liquid convective heat transfer regime, to a subcooled and saturated nucleate boiling heat transfer regime, to a forced convection evaporative heat transfer regime, and finally to a forced vapor convective heat transfer regime. In the liquid convective heat transfer regime, the feedwater is heated such that the local fluid temperature approaches (but does not reach) the local saturation temperature. As such, little if any feedwater boiling occurs in the liquid convective heat transfer regime, and the liquid convective heat transfer regime is generally not associated with generator fouling. In the nucleate boiling heat transfer regime, heat flux through the super heated surface induces feedwater boiling at discrete locations on the surface (*e.g.* at surface micro-cavities or other small-scale surface deformations). These phenomena are associated with scale deposition and steam generator fouling, as the liquid-vapor transition occurs on the surface of the boiler tube. In the forced convection



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evaporative heat transfer regime, the majority of the liquid-vapor transition occurs away from the surface, as the surface is substantially covered by a non-boiling layer (*i.e.* a liquid or vapor film). Like the liquid convective heat transfer regime, the forced convection evaporative heat transfer regime is associated with a lower rate of fouling. Nucleate boiling has accordingly long been recognized not as an avoidable problem, but as an inherent consequence of the thermodynamic imperatives of steam generation.

**[0006]** Steam generator fouling is also associated with steam generation under dryout conditions. Briefly stated, dryout conditions are thought to occur when the liquid inventory of a stream is not sufficient to maintain wetted conditions along the heat-transfer surface. Dryout conditions are generally associated with high steam qualities and high-velocity flowrates. Under dryout conditions, the liquid inventory may be carried in the bulk flow as a mist and any liquid droplets that do manage to contact the wall are likely to evaporate on contact thereby depositing previously dissolved materials onto the heat-transfer surface.

## SUMMARY

**[0007]** The present disclosure recognizes that there is an unmet need for new, alternate, and/or improved methods and systems for generating steam from produced water, especially for produced water that is de-oiled but otherwise untreated (or minimally treated). The methods and systems disclosed herein utilize a two-stage steam generation strategy that attenuates steam generator fouling by mitigating (*i.e.* reducing or eliminating) nucleate boiling on super heated surfaces within the steam generator.

**[0008]** In the first stage, a feedwater stream is pressurized and heated to a first pressure/temperature condition. These first pressure and temperature conditions may optionally be selected so that the feedwater is sufficiently subcooled to ensure that the localized heat flux is not sufficient to induce nucleate boiling (subcool is the difference between the saturation temperature (boiling point) of the feedwater at a given pressure and the lower actual temperature of the feedwater at the given pressure). Under such a condition, heat transfer occurs by forced liquid convection. The second stage – and the transition from the first stage to the second stage – is configured to ensure a near instantaneous transition to a condition above a threshold steam quality. As set out in detail below, staying above a threshold steam quality prioritizes forced convective evaporation such that nucleate boiling is not a dominant heat-transfer mechanism.



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**[0009]** The present disclosure is based on state-of-the-art modelling which, after extensive research and development, elucidate two unique approaches to generating steam while mitigating nucleate boiling. In one approach, as the feedwater stream approaches the saturated nucleate boiling regime, an auxiliary-steam stream is utilized to boost the steam quality above the threshold steam quality and into the convective evaporative heat transfer regime. In the other approach, an atypical flow-path is coupled with a pressure-reducing element to the same effect. Importantly, as set out in detail below, incorporating a pressure-reducing element into a conventional flow path is unlikely to satisfy the tolerances associated with steam generation for hydrocarbon recovery. The combination of a pressure-reducing element and a particular type of flow path is required in the absence of an auxiliary-steam stream.

**[0010]** The two approaches can also be combined and, whether taken alone or together, they allow for efficient steam generation while attenuating steam generator fouling. As such, the methods and systems of the present disclosure may be suitable for generating steam from produced water that is de-oiled but otherwise untreated or minimally treated. Such methods and systems could be used to extend the operating time between cleanings for existing operations with more fully treated water.

<u>Approach 1: Utilizing an auxiliary-vapour stream</u>

**[0011]** One general aspect includes a method of generating steam for use in a hydrocarbon production process, the method including: pressurizing a feedwater stream to a first feedwater pressure condition and heating the feedwater stream to a first feedwater temperature condition, to provide a heated feedwater stream. The method of generating steam also includes combining the heated feedwater stream with an auxiliary vapour stream to form a vapour-enhanced stream having a controlled vapour-enhanced steam quality at a second vapour-enhanced temperature condition and a second vapour-enhanced pressure condition. The method of generating steam also includes heating the vapour-enhanced stream in a steam generator to increase the steam quality thereof to provide a heated vapour-enhanced steam stream, where the controlled vapour-enhanced steam quality at the second temperature condition and the second pressure condition is maintained so as to mitigate nucleate boiling on a heated steam generator surface within the steam generator during the heating of the vapour-enhanced stream. The method of generating steam also includes injecting at least a portion of the heated vapour-enhanced



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steam stream into a hydrocarbon-containing reservoir as an injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

**[0012]** One general aspect includes a system for generating steam for hydrocarbon production, the system including: a pressurizing element that is configured to pressurize a feedwater stream to a first feedwater pressure condition, to provide a pressurized feedwater stream. The system also includes a convective-heating section configured to heat the pressurized feedwater stream to a first feedwater temperature condition, to provide a heated feedwater stream. The system also includes a stream connector that is configured to combine the heated feedwater stream with an auxiliary vapour stream to form a vapour-enhanced stream having a controlled vapour-enhanced steam quality at a second vapour-enhanced temperature condition and a second vapour-enhanced pressure condition. The system also includes a radiant-heating section configured to heat the vapour-enhanced stream in a steam generator to increase the steam quality thereof to provide a heated vapour-enhanced steam stream, where the controlled vapour-enhanced steam quality at the second temperature condition and the second pressure condition is maintained so as to mitigate nucleate boiling on a heated steam generator surface within the steam generator during the heating of the vapour-enhanced stream. The system also includes a steam injection section configured to inject at least a portion of the heated vapour-enhanced steam stream into a hydrocarbon-containing reservoir as an injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

**[0013]** Implementations may include one or more of the following features. The method and/or system where the auxiliary vapour stream includes an auxiliary steam. The method and/or system where the auxiliary steam has a steam quality of greater than about 90%. The method where the auxiliary steam has a temperature of between about 200°C and 350°C, or between about 212°C and about 311°C. The method and/or system where the auxiliary steam has an auxiliary steam pressure of between about 2 MPa and about 10 MPa. The method and/or system where the auxiliary steam includes steam generated in a separate boiler from a treated water stream. The method and/or system where the auxiliary vapour stream includes one or more of a fuel gas, a produced gas, an inert gas, or an oxygen-free gas mixture. The method and/or system where the first feedwater pressure condition is between about 12 MPa and about 15 MPa, or at least about 12,500 kPa, or at least about 14,500 kPa. The method and/or system where the second vapour-enhanced pressure condition is at least about 3,500 kPa or at least about 5,000 kPa, or at least about



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9,500 kPa, or between about 3 MPa and about 12 MPa. The method and/or system where the second vapour-enhanced temperature condition is between about 200°C and about 350°C, or between about 234°C and about 325°C. The method and/or system where heating the vapour-enhanced steam stream includes providing a peak heat flux of between about 150 kW/m$^2$ and about 300 kW/m$^2$ and/or providing an average heat flux of between about 50 kW/m$^2$ and about 160 kW/m$^2$ (on an inside area basis). The method and/or system where heating the feedwater stream to the first feedwater temperature condition includes heating to a controlled subcooled feedwater temperature so as to mitigate nucleate boiling at the first feedwater pressure condition. The method and/or system where the controlled subcooled feedwater temperature is at least about 3ºC, 10ºC, 20ºC, 22ºC, 30ºC or 40ºC subcooled. The method and/or system where the controlled subcooled feedwater temperature is subcooled by a subcool, ΔT, that satisfies the following condition:

$$\Delta\mathrm{T} \geq \frac{q}{0.023{R_e}^{0.8}{P_r}^{0.4}\frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

wherein:

$q$ is the local heat flux expressed in W/m$^2$,

$R_e$ is the Reynolds number,

$P_r$ is the Prandtl number,

$k$ is the fluid thermal conductivity expressed in W/m/°C,

$D_e$ is the hydraulic diameter, and

$P$ is the system pressure expressed in Pa.

**[0014]** The method and/or system may also include heating the feedwater stream to the first feedwater temperature condition includes maintaining a peak feedwater heat flux of less than 50 kW/m$^2$ (on an inside area basis). The method and/or system where heating the feedwater stream to the first feedwater temperature condition includes providing a first heating mass flux rate of between about 800 kg/m$^2$/s and about 2,500 kg/m$^2$/s. The method and/or system where heating the feedwater stream to the first feedwater temperature condition includes heating the feedwater stream in an economizer section of the steam generator. The method and/or system where the controlled vapour-enhanced steam quality is at least about 3 %, at least about 5 %, at least about 12 %, or between about 10 % and about 30 %. The method where the heated vapour-enhanced steam stream has a heated



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vapour-enhanced steam quality of at least about 70 %, at least about 80 %, or at least about 90 %. The method where the controlled vapour-enhanced steam quality, x, is controlled so as to satisfy the following condition:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}}+1}$$

wherein:

$q$ is the local heat flux expressed in W/m$^2$,

$G$ is the mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is the evaporative enthalpy expressed in J/kg,

$\rho_G$ is the vapour density expressed in kg/m$^3$,

$\rho_L$ is the liquid density expressed in kg/m$^3$,

$\mu_L$ is the vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is the liquid phase dynamic viscosity expressed in Pa·s, and,

$B_i$ is the boiling index and is ≤ 0.00015, or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

**[0015]** The method/system where the steam quality of the heated vapour-enhanced steam stream is controlled to satisfy the following condition:

$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We_G}^{0.17}Fr_G^{0.37}\left(\frac{\rho_G}{\rho_L}\right)^{0.25}\left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$

$$Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G)\mathrm{g}D_E};$$



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$$q_{DNB} = 0.131\rho_G^{0.5} h_{fg} (g(\rho_L - \rho_G)\sigma)^{0.25}$$

and wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in kg/m$^3$);

$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

$\sigma$ is the surface tension (expressed in N/m).

**[0016]** The method and/or system may be carried out/configured so that at least a portion of the heated vapour-enhanced steam stream is recycled to the auxiliary vapour stream as a recycled steam stream. The method and/or system where between about 3% and about 30% by weight, or between about 5% and about 20% by weight, of the heated vapour-enhanced steam stream is recycled to the auxiliary-vapour stream as the recycled steam stream. The method and/or system where the recycled steam stream is compressed before being combined with the heated feedwater stream. The method further including separating the heated vapour-enhanced steam stream into a substantially vapour-phase stream and a substantially liquid-phase stream prior to injection of at least a first portion of the substantially vapour-phase stream into the hydrocarbon-containing reservoir. The method and/or system where a second portion of the substantially vapour-phase stream is recycled to the auxiliary vapour stream as a recycled steam stream. The method and/or system where the second portion of the substantially vapour-phase stream accounts for between about 3% and about 30% by weight of the substantially vapor-phase stream. The method and/or system where the substantially vapor-phase stream accounts for between about 70% and about 95 %, or between about 80% and about 90%, by weight of the heated



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vapour-enhanced steam stream. The method and/or system where the substantially liquid-phase stream accounts for between about 30% and about 5%, or between about 20% and about 10%, by weight of the heated vapour-enhanced steam stream. The method and/or system where the controlled injected steam quality is at least about 80%, at least about 85%, at least about 90%, at least about 95% or about 100%. The method and/or system where the hydrocarbon-containing reservoir is a bitumen-containing reservoir. The method and/or system where the hydrocarbon production process includes steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof. The method and/or system where the hydrocarbon production process includes a SAGD process, the controlled injected steam quality is between about 85 % and about 100 %, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250 °C and about 325 °C. The method and/or system where the steam generator is heat-recovery steam generator (HRSG). The method and/or system where the HRSG is a natural-circulation steam generator (NCSG), forced-circulation steam generator (FCSG), or once-through steam generator (OTSG). The method and/or system where the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L. The method and/or system where the feedwater stream has a hardness content of less than about 25 mg/l, or less than about 15 mg/L. The method and/or system where the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L. The method and/or system where the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L. The method and/or system where the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L. The method and/or system where the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU. The method and/or system where the heating of the feedwater stream to the first feedwater temperature condition occurs primarily by convective heating and/or substantially in the absence of nucleate boiling. The method and/or system where the heating of the vapour-enhanced steam stream occurs primarily by radiative heating and/or substantially in the absence of nucleate boiling. The method and/or system where combining the heated feedwater stream with the auxiliary vapour stream is carried out in an eductor having a motive-fluid inlet, a passive-fluid inlet, and a discharge outlet. The method and/or system where the feedwater stream enters the eductor at the motive fluid inlet, the auxiliary-vapour stream enters the eductor at the passive-fluid inlet, and the vapour-enhanced stream exits the eductor at the discharge outlet.



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Approach 2: Utilizing a novel flow-path configuration in combination with a pressure-reducing element

**[0017]** One general aspect includes a method of generating steam for use in a hydrocarbon production process, the method comprising: passing a feedwater stream from a first-stage inlet to a first-stage outlet along a first-stage flow path, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-temperature is maintained below the saturation temperature of the feedwater stream, and (iv) the first-stage flow path is configured to attenuate the first-stage heat flux as the feedwater stream approaches the first-stage outlet. The method further comprises passing the feedwater stream from the first-stage outlet through a pressure-reducing element to a second-stage inlet, wherein the second-stage inlet has a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream. The method further comprises passing the flashed stream from the second-stage inlet to a second-stage outlet along a second-stage flow path, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream. The method further comprises injecting at least a portion of the flashed stream into a hydrocarbon-containing reservoir as injected steam to facilitate the hydrocarbon production process.

**[0018]** One general aspect includes a system for generating steam for a hydrocarbon production process, the system comprising: (i) a radiant section, (ii) an economizer having a lower section that is proximal to the radiant section and an upper section that is proximal to the lower section, and (iii) a combustion-gas flow path that passes from the radiant section to the lower section of the economizer to the upper section of the economizer. The system further comprises a first-stage flow path for passing a feedwater stream through at least a portion of the steam generator from a first-stage inlet to a first-stage outlet, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure by a pressurizing element, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-temperature is maintained below the saturation temperature of the feedwater stream, and (iv) at least part of the first-stage flow path is co-current with the combustion-gas flow path as the feedwater stream



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approaches the first-stage outlet. The system further comprises a pressure-reducing element that connects the first-stage outlet to a second-stage inlet, wherein the pressure-reducing element is configured to reduce the first-stage pressure to a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream. The system further comprises a second-stage flow path for passing the flashed stream through at least a portion of the steam generator from the second-stage inlet to a second-stage outlet, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream. The system further comprises a steam injection section configured to inject at least a portion of the flashed steam stream into a hydrocarbon-containing reservoir as injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

**[0019]** Implementations may include one or more of the following features. The method and/or system where the first-stage flow path is co-current with a combustion-gas flow path as the feedwater stream approaches the first-stage outlet. The method and/or system where, as the feedwater stream approaches the first-stage outlet, the first-stage flow path comprises bare tube. The method and/or system where the feedwater stream approaches the first-stage outlet in a lower section of an economizer. The method and/or system where the feedwater stream approaches the first-stage outlet after passing through a radiant section. The method and/or system where the feedwater stream passes through an upper section of an economizer before passing through the radiant section. The method and/or system where, as the first-stage flow path passes through the radiant section, the first-stage average heat flux is between: (i) about 40 $kW/m^2$ and about 100 $kW/m^2$; and/or (ii) about 50 $kW/m^2$ and about 90 $kW/m^2$, on an inside area basis. The method and/or system where, as the first-stage flow path passes through the shock row of the lower section of the economizer, the first-stage average heat flux in the lower section is between: (i) about 65 $kW/m^2$ and about 135 $kW/m^2$; and/or (ii) about 75 $kW/m^2$ and about 120 $kW/m^2$, on an inside basis. The method and/or system where, as the first-stage flow path passes through the fifth row of the lower section of the economizer, the first-stage average heat flux in the lower section is between: (i) about 25 $kW/m^2$ and about 75 $kW/m^2$; and/or (ii) about 35 $kW/m^2$ and about 65 $kW/m^2$, on an inside basis. The method and/or system where, as the first-stage flow path passes through the first finned row in the upper section of the



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economizer, the first-stage average heat flux in the upper section is between: (i) about 85 kW/m$^2$ and about 220 kW/m$^2$; and/or (ii) about 110 kW/m$^2$ and about 200 kW/m$^2$, on an inside basis. The method and/or system where, as the first-stage flow path passes through the last finned row in the upper section of the economizer, the first-stage average heat flux in the upper section is between: (i) about 2 kW/m$^2$ and about 12 kW/m$^2$; and/or (ii) about 3 kW/m$^2$ and about 10 kW/m$^2$, on an inside basis..

**[0020]** The method and/or system where the steam quality of the flashed stream is controlled to satisfy the following condition:

$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We_G}^{0.17} Fr_G^{0.37}\left(\frac{\rho_G}{\rho_L}\right)^{0.25}\left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$

$$Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G)\mathrm{g}D_\mathrm{E}};$$

$$q_{DNB} = 0.131\rho_G^{0.5} h_{fg}(\mathrm{g}(\rho_L - \rho_G)\sigma)^{0.25}$$

and where:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in kg/m$^3$);



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$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

σ is the surface tension (expressed in N/m).

**[0021]** The method and/or system where the first-stage pressure is between about 15 MPa and about 22 MPa. The method and/or system where second-stage pressure is between about 4 MPa and about 11 MPa. The method and/or system where the first-stage temperature is between about 340 ºC and about 360 ºC at the first-stage outlet. The method and/or system where the first-stage temperature is at least about 3 ºC, 10 ºC, 15 ºC, or 20 ºC subcooled as the feedwater stream approaches the first-stage outlet. The method and/or system where as the feedwater stream approaches the first-stage outlet the first-stage temperature is subcooled by a subcool, $\Delta T$, that satisfies the following condition:

$$\Delta T \geq \frac{q}{0.023{R_e}^{0.8}{P_r}^{0.4}\frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

where:

$q$ is a local heat flux expressed in W/m$^2$,

$R_e$ is a Reynolds number,

$P_r$ is a Prandtl number,

$k$ is a fluid thermal conductivity expressed in W/m/°C,

$D_e$ is a hydraulic diameter, and

$P$ is a system pressure expressed in Pa.

**[0022]** The method and/or system where the steam quality of the flashed stream at the second-stage inlet is at least about 3 %, at least about 5 %, at least about 12 %, or between about 10 % and about 20 %. The method and/or system where the flashed stream has a steam quality of at least about 70%, at least about 80%, or at least about 90% at the second-stage outlet. The method and/or system where the steam quality, $x$, of the flashed stream is controlled so as to satisfy the following condition at the second-stage inlet:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}} + 1}$$

wherein:



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$q$ is a local heat flux expressed in W/m$^2$,

$G$ is a mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is a evaporative enthalpy expressed in J/kg,

$\rho_G$ is a vapour density expressed in kg/m$^3$,

$\rho_L$ is a liquid density expressed in kg/m$^3$,

$\mu_L$ is a vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is a liquid phase dynamic viscosity expressed in Pa·s, and

$B_i$ is a boiling index and is ≤ 0.00015, or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

**[0023]** The method and/or system where the steam quality of the portion of the flashed stream that is injected into the hydrocarbon-containing reservoir is at least about 80%, at least about 85%, at least about 90%, at least about 95%, or about 100%. The method and/or system where hydrocarbon-containing reservoir is a bitumen-containing reservoir. The method and/or system where the hydrocarbon production process comprises steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof. The method and/or system where the hydrocarbon production process comprises a SAGD process, the controlled injected steam quality is between about 85% and about 100%, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250 °C and about 325 °C. The method and/or system where the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L. The method and/or system where the feedwater stream has a hardness content of less than about 25 mg/L, or less than about 15 mg/L. The method and/or system where the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L. The method and/or system where wherein the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L. The method and/or system where the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L. The method and/or system where the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU.



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## BRIEF DESCRIPTION OF THE DRAWINGS

**[0024]** These and other features of the present disclosure will become more apparent in the following detailed description in which reference is made to the appended drawings. The appended drawings illustrate one or more embodiments of the present disclosure by way of example only and are not to be construed as limiting the scope of the present disclosure.

**[0025]** **FIG. 1** provides a schematic plot of various heat transfer mechanisms as the water passes through a heated boiler tube.

**[0026]** **FIG. 2** provides a schematic of a system for generating steam for a thermal process for hydrocarbon recovery in accordance with select embodiments of the present disclosure.

**[0027]** **FIG. 3A** provides a schematic of an eductor which may be utilized as a stream connector and a pressure-reducing element in accordance with select embodiments of the present disclosure. **FIG. 3B** provides estimated ideal discharge parameters from the eductor of **FIG. 3A**. **FIG. 3C** provides parameters relating to the quantity of the auxiliary-vapour stream, relative to the feedwater stream inlet flow rate. **FIG. 3D** provides parameters relating to the quantity of (simple) flash steam created by reducing the feedwater-stream pressure to the steam-enhanced stream pressure at the outlet of the eductor in the absence of any contribution from the auxiliary-vapour stream.

**[0028]** **FIG. 4** provides a plot of heat flux at the transition into the nucleate boiling heat transfer regime as a function of the difference between the local fluid temperature and the local saturation temperature (*i.e.* the degree of subcool) for a series of different saturation temperatures.

**[0029]** **FIG. 5** provides a plot of heat flux at the transition out of the nucleate boiling regime as a function of steam quality at the transition out of the nucleate boiling heat transfer regime for a series of different saturation temperatures and fluid flow rates.

**[0030]** **FIG. 6** provides a scatter plot of typical normal peak operating heat flux values based on the external surface area of the finned-tube component of an archetypal boiler or HRSG.



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**[0031]** **FIG. 7** provides a scatter plot of peak heat flux values on an inside area of the finned-tube component of an archetypal boiler or HRSG.

**[0032]** **FIG. 8** provides a scatter plot of typical normal peak operating heat flux values based on the external surface area for radiant and shock tube components of typical boiler or HRSG.

**[0033]** **FIG. 9** provides a scatter plot of peak heat flux values for the same configurations on an inside area basis diameter for radiant and shock tube components of typical boiler or HRSG.

**[0034]** **FIG. 10** provides a plot of the maximum subcool required for subcooled nucleate boiling for NPS 3 S160 pipe coil under archetypal conditions.

**[0035]** **FIG. 11** provides a further plot of the maximum subcool required for subcooled nucleate boiling for NPS 3 S160 pipe coil under archetypal conditions.

**[0036]** **FIG. 12** provides a plot of the minimum steam quality required for forced convective evaporation under archetypal conditions.

**[0037]** **FIG. 13** provides a plot of the minimum steam quality required for forced convective evaporation under archetypal conditions.

**[0038]** **FIG. 14** shows a schematic of an OTSG configured with a novel flow-path in combination with a pressure-reducing element in accordance with a method and/or system of the present disclosure.

**[0039]** **FIG. 15A** and **FIG. 15B** show plots of feedwater stream flowrate as a function of steam quality at dryout based on a steam-injection temperature at about 310 ºC for two common coils.

**[0040]** **FIG. 16A** and **FIG. 16B** show plots of flowrate as a function of minimum steam quality for an archetypal set of steam-generator parameters.

**[0041]** **FIG. 17A – FIG. 17D** show plots of steam quality at the second-stage inlet as a function of the first-stage pressure for an archetypal set of steam-generator parameters.



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**[0042]** **FIG. 18A** and **FIG. 18B**, show plots of minimum subcool as a function of heat flux at first-stage pressures for an archetypal set of steam-generator parameters.

**[0043]** **FIG.19** shows plots of heat flux across a set of economizer rows (1 = shock row) for a series of archetypal heat-release profiles.

**[0044]** **FIG. 20** shows plots of various operating conditions in the context of a conventional OTSG design.

**[0045]** **FIG. 21** shows plots of various operating conditions in the context an OTSG configured with a novel flow-path in combination with a pressure-reducing element in accordance with a method and/or system of the present disclosure.

## DETAILED DESCRIPTION

**[0046]** Thermal processes for hydrocarbon recovery often require high-quality, high-temperature, and high-pressure steam. For example, SAGD processes may employ steam having a quality of between about 85 % and about 100 %, a pressure of between about 4,000 kPa and about 11,000 kPa, and a temperature of between about 250 °C and about 325 °C. Heat-recovery steam generators (HRSG(s)) are often used to provide steam for such processes. HRSG(s) are typically classified as forced-circulation steam generators (FCSG(s)), or once-through steam generators (OTSG(s)). Because OTSGs are the type of HRSG that is most commonly used in hydrocarbon recovery operations, the methods and systems of the present disclosure are discussed within OTSG-related frameworks. However, those skilled in the art having benefited from the teachings of the present disclosure will appreciate how the methods and systems of the present disclosure apply to NCSGs, FCSGs, or HRSGs more generally.

**[0047]** OTSGs are large, continuous-tube type steam generators. Feedwater is supplied at one end of the tube, and it is heated (and eventually converted to steam) as it travels in a single pass along the tube. OTSGs typically comprises of a multitude of parallel flow passes to accommodate the total flowrate within a given tube size. OTSGs typically comprise of a convection section (also called an economizer section or an economizer) and a radiant section. In the convection section, the feedwater is preheated by heat exchange with a hot combustion gas (usually flue gas). In the radiant section, the feedwater is heated more aggressively by a high-powered furnace.



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**[0048]** The methods and systems disclosed herein utilize a two-stage steam generation strategy that attenuates steam generator fouling by mitigating (*i.e.* reducing or eliminating) nucleate boiling on super heated surfaces within the steam generator. In the first stage, operational parameters are controlled to ensure the feedwater stream is pressurized and heated under conditions that are not sufficient to induce subcooled nucleate boiling. The subcool of the feedwater stream (*i.e.* the difference between the local temperature of the feedwater stream and its local saturation temperature) in the economizer section is a critical parameter in this respect. The subcool of the feedwater stream is selected to ensure heat transfer occurs by convective heat transfer. In the second stage, operational parameters are controlled to ensure that heating in the radiant section occurs by forced convective evaporation such that the saturated nucleate boiling regime is substantially avoided. The steam quality of the fluid is a critical parameter in this respect.

**[0049]** The present disclosure provides two approaches to generating steam while mitigating nucleate boiling. In one approach, as the feedwater stream approaches the saturated nucleate boiling regime, an auxiliary-steam stream is utilized to boost the steam quality above the threshold required to enter the convective evaporation heat transfer regime. In the other approach, an atypical flow-path is coupled with a pressure-reducing element to the same effect. While the two approaches can be combined, the present disclosure outlines them independently for sake of clarity. Those skilled in the art having benefited from the teachings of the present disclosure will appreciate how the two approaches can be combined in one steam generator. While the two approaches are outlined independently, there is substantial overlap between the two approaches – many of the teachings (e.g. terms, concepts, equations, and/or the like) set out for one approach may apply to the other. Those skilled in the art having benefited from the teachings of the present disclosure will readily appreciate such overlaps and how they can be applied to practice the systems and methods of the present disclosure.

**[0050]** Select embodiments of the present disclosure will now be described with reference to **FIG. 1** – **FIG. 30**. **FIG. 1** – **FIG. 30** illustrate aspects of one or more embodiments of the present disclosure by way of example only and are not to be construed as limiting the scope of the present disclosure.



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Approach 1: Utilizing an auxiliary-vapour stream

**[0051]** Select embodiments of the systems and methods of the present disclosure utilize an auxiliary-vapour stream to meet or exceed the threshold for film boiling at the second pressure/temperature condition. The feedwater stream and the auxiliary-vapour stream are connected in a “stream connector” which may be a simple 3-way connector, a valve, a pressure reducer (such as eductor), or the like. Analysis shows that absent an enhancement in steam quality from the auxiliary-vapour stream (or a substantial reconfiguration of the flow path), substantial pressure drops are required to obtain sufficient steam quality to ensure forced convective evaporation under typical operation conditions. Such pressure drops may not be feasible from an operations perspective and/or they may be excessively inefficient. By utilizing the auxiliary-vapour stream in the second stage, the systems and methods of the present disclosure provide a means of minimizing or eliminating the pressure drop required at the second stage. This provides for improved energetic efficiencies and allows for greater latitude in setting the parameters of the first stage. Taken together, the first stage and the second stage provide a process with improved efficiency for generating steam from feedwater streams that would not be suitable for steam generation using standard protocols.

**[0052]** Select embodiments of the present disclosure relate to a feedwater stream. The feedwater stream may comprise fluids from a produced emulsion that has been subjected to coarse oil-water separation (such as by degassing, treating, and/or free water knockout), or not. Optionally, fluids from the produced emulsion may be de-oiled but otherwise untreated to form the feedwater stream. Alternatively, fluids from the produced emulsion may be minimally treated, or heavily treated. In the context of the present disclosure, de-oiling may involve passing fluids from the produced emulsion through a gravity separator (such as a skim tank), a flotation-type unit (such as a compact flotation unit), and/or a filtration-type unit (such as an oil removal filter).

**[0053]** In select embodiments, the feedwater stream may have a residual oil content of less than about 200 mg/L (preferably less than about 2.0 mg/L). The feedwater stream may have a turbidity of less than about 250 NTU ppm (preferably less than about 5 NTU). The feedwater stream may have a silica content of less than about 250 mg/L (preferably less than about 50 mg/L). The feedwater stream may have a hardness content of less than about 25 mg/L (preferably less than about 15 mg/L). The feedwater stream may have a total suspended solids content of less than about 200 mg/L (preferably less



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than about 5 mg/L). The feedwater stream may have a soluble organics content of less than about 500 mg/L (preferably less than about 400 mg/L). Those skilled in the art having benefited from the teachings of the present disclosure will readily appreciate the standard techniques and equipment used to determine the residual oil content, the turbidity, the silica content, the hardness content, the total suspended solids content, and/or the soluble organics content of a feedwater stream.

**[0054]** In select embodiments of the present disclosure, the feedwater stream is pressurized to a first pressure condition that is in part dependent upon the second pressure condition, in the sense that the difference between the first and second pressure conditions will provide the available scope for flash steam generation by pressure reduction. For example, assuming a second pressure condition of approximately 9,500 kPa, the first pressure condition feedwater may have a pressure of at least about 12,500 kPa (preferably at least about 14,500 kPa), to yield a desired amount of flash steam. In the context of present disclosure, the feedwater may be pressurized to the first pressure condition by a pressurizing element such as a pump. The system pressure is increased to the extent that the feedwater can remain in liquid phase without boiling when being heated. Also, the system pressure may only be increased to the extent commercially feasible with existing piping components and materials. In select embodiments of the present disclosure, the use of solvents and/or generation of the steam at a pad for injection (instead of at a central processing facility) may require lower pressure steam such that the second pressure condition may be at least about 5,000 kPa or at least about 3,500 kPa.

**[0055]** In select embodiments of the present disclosure, the feedwater stream may be heated to a first temperature condition. The first temperature condition is referenced by the subcool temperature. The subcool temperature is the difference between the boiling point temperature at the local operating pressure and the bulk fluid temperature. At the first temperature condition, the feedwater may have a subcool temperature of between about 10 °C and about 40 °C (preferably between about 20 °C and about 30 °C). Heating the feedwater stream to the first temperature condition may comprise providing a peak heat flux of between about 150 kW/m$^2$ and about 300 kW/m$^2$ (on an inside area basis). In the context of the present disclosure, "heat flux" is the rate of heat energy transfer through a given surface, in other words, the heat rate per unit area on an inside surface area basis. As will be appreciated by those skilled in the art having benefited from the teachings of the present disclosure, there may be variation of the heat flux around the circumference of the



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tube, as well as along the longitudinal axis – and the peak heat flux refers to the maximum local heat flux at a given point along the circumference. Another measure is the average heat flux, which typically refers to the local average heat flux around the circumference. Typically, the local peak heat flux is 1.4 to 2.6 times the average heat flux, depending on tube geometry and other factors.

**[0056]** Heating the feedwater stream to the first temperature condition may occur primarily by forced convective heating. Heating the feedwater stream to the first temperature condition may occur in a convective-section of a steam generator such as in an economizer. In the context of the present disclosure, an economizer comprises one or more devices configured to reduce energy consumption in a steam-generating operation by preheating feedwater. Typically, an economizer comprises a heat exchanger in which thermal energy is transferred from a high-temperature fluid (*e.g.*, steam condensate or flue gas) to the feedwater such that less energy is required to vaporize it. Economizers may be mechanical devices intended to reduce energy consumption or to perform another useful functions such as preheating a fluid. Economizers are typically fitted to a boiler, and they may save energy by using, for example, the exhaust gases from the boiler to preheat cold feedwater. In the context of the present disclosure, the economizer may occur downstream of the pressurizing element, or the economizer and the pressurizing element may be integrated.

**[0057]** As will be appreciated by those skilled in the art having benefited from the teachings of the present disclosure, economizers typically use extended heat transfer surfaces, such as solid or serrated fins, to improve the heat extraction from the hot fluid. The tubes in contact with the hottest fluid are typically bare tubes, and fins are provided to the outside of the tubes to increase the local heat flux at points contacting the hot fluid after the initial heat transfer to the bare tubes. Fins are available in a multitude of diameters and spacing and can be selected to manage heat flux rate throughout the economizer. The location of subcooled boiling is a function of the local peak heat flux, the thermo-physical properties of the fluid, the fluid velocity, tube diameter, and the amount of subcool of the fluid. High local peak heat flux requires a larger amount of subcool than a lower local peak heat flux with all other variables equal, to prevent subcooled nucleate boiling. By judicious use of fin profiles throughout the economizer, the local peak heat flux can be managed to maintain sufficient subcool temperature to prevent subcooled boiling and the associated high fouling rate.



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**[0058]** In select embodiments of the present disclosure, at the first temperature condition, the feedwater stream operates at a maximum temperature such that the subcool is at least about 10 °C (preferably by between about 20 °C and about 30 °C) to substantially prevent subcooled nucleate boiling. The extent of subcool of a feedwater stream and the operational parameters required to substantially prevent nucleate boiling may be determined, for example, using the Bergles-Rohsenow correlation, the Yin correlation, the Thom correlation, the Dittus-Boelter correlation, the Sieder-Tate correlation, the Gnielinski correlation, or any other appropriate correlation or combination thereof. In select embodiments of the present disclosure, one or more of the foregoing correlations may be used in a form suitable for a single phase or a two-phase (liquid/gas) system.

**[0059]** The onset of nucleate boiling (ONB) temperature is generally determined by the solution of two equations. One equation relates the heat flux at ONB to the wall superheat (*i.e.* the difference between the temperature of the inside pipe surface and the local saturation boiling point of the water). The second equation relates the heat flux to the difference between the inside pipe wall temperature and the bulk fluid temperature, the flowing conditions and thermo-physical properties of the fluid, and the tube geometry. Two such equations are the Bergles-Rohsenow and the Dittus-Boelter equation.

**[0060]** The Bergles-Rohsenow equation provides a relationship between the heat flux ($q$), and the wall superheat at the ONB. The Bergles-Rohsenow correlation is shown in **EQN. 1**.

$$q = .00176P^{1.156}\left\{\frac{9}{5}(T_w - T_s)\right\}^{\frac{2.83}{P^{0.0234}}} \quad \textbf{EQN. 1}$$

wherein: $T_w$ and $T_s$ are the inside wall temperature and local saturation temperature (in °C) respectively; q is the heat flux necessary to cause nucleate boiling (in W/m$^2$); and $P$ is the system pressure (in Pa).

**[0061]** The Dittus-Boelter correlation provides a relationship between the heat flux (q) and the temperature difference between the pipe wall ($T_w$) and the bulk fluid temperature ($T_b$). The Dittus-Boelter correlation is shown in **EQN. 2**.

$$q = 0.023\, R_e{}^{0.8}\, P_r{}^{0.4}\, \frac{k}{D_e}\{(T_w - T_s) + (T_s - T_b)\} \qquad \textbf{EQN. 2}$$



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wherein: $q$ is the local heat flux (in W/m$^2$), $R_e$ is the Reynolds number, $P_r$ is the Prandtl number, $k$ is the fluid thermal conductivity (in W/m/°C), $D_e$ is the hydraulic diameter, which is the inside diameter for pipe (in m), $T_w$, $T_s$ and $T_b$ are the wall temperature, saturation temperature and bulk fluid temperature (in °C) respectively. The fluid properties are evaluated at the film temperature, which is defined in **EQN 3**.

$$T_f = \frac{T_w + T_b}{2} \qquad \textbf{EQN. 3}$$

wherein: $T_f$, $T_w$ and $T_b$ are the film temperature, wall temperature and bulk fluid temperature (in °C) respectively.

**[0062]** Select embodiments of the present disclosure comprise combining the feedwater stream with an auxiliary-vapour stream to form a vapour-enhanced stream at a second pressure condition and a second temperature condition. The vapour-enhanced stream may have a steam quality of at least about 3 % (preferably at least about 5 %) to mitigate against nucleate boiling during further heating. At the second pressure condition, the vapour-enhanced stream may have a pressure of between about 3 MPa and about 12 MPa. At the second temperature condition, the vapour-enhanced stream may have a temperature of between about 234 °C and about 325 °C. Prior to combining the feedwater stream with the auxiliary-vapour stream, the auxiliary-vapour stream may have a pressure of between about 2 MPa and about 10 MPa. Prior to combining the feedwater stream with the auxiliary-vapour stream, the auxiliary-vapour stream may have a temperature of between about 212 °C and about 311 °C. Prior to combining the feedwater stream with the auxiliary-vapour stream, the auxiliary-vapour stream may have a steam quality of between about 90 % and about 100 %.

**[0063]** **EQN. 2** indicates that heat flux increases with increasing fluid velocity (*i.e.* an increasing Reynolds number) and with increasing bulk fluid subcool operating temperature (*i.e.* $(T_s - T_b)$). For a given wall superheat, operating flowrate, pressure and geometry, the bulk fluid subcool temperature can be determined that will result in the onset of nucleate boiling.

**[0064]** In select embodiments of the present disclosure, the combining of the feedwater stream with the auxiliary-vapour stream to form the vapour-enhanced stream at the second pressure condition and the second temperature condition may be couple with a pressure reduction facilitated by a pressure reducing agent such as an eductor. Those



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skilled in the art having benefited from the teachings of the present disclosure will appreciate that eductors are used in other industry processes and often referred to by alternate names such as “ejector”, “jet compressor” and “jet pump”. In the context of the present disclosure, an eductor is a device that combines a motive fluid (under a higher pressure condition) with a passive fluid (at a lower pressure condition) and discharges the fluids as a mixture of the fluids (at a pressure between the motive fluid pressure and the passive fluid pressure). In the context of the present disclosure the terms “eductor”, “ejector”, “jet compressor”, and/or “jet pump” do not imply any particular phase of the motive fluid and/or the passive fluid.

**[0065]** In select embodiments of the present disclosure, the eductor is configured such that at least a portion of the feedwater stream is converted to flash steam. In the context of the present disclosure, "flash steam" refers to steam formed when high-temperature condensate is subjected to a rapid pressure reduction. Those skilled in the art having benefited from the teachings of the present disclosure will recognize that flash steam is just a convenient name used to explain how the steam is formed, and that it does not imply a unique steam composition. Briefly stated, high temperature condensate stores latent energy that cannot be retained at lower pressure. When subjected to a pressure drop, some of the excess energy causes a percentage of the condensate to flash to the vapor phase. This process contributes to the steam quality of the steam-enhanced stream which may provide operational flexibility with respect to the parameters associated with the contribution from the auxiliary-vapour stream.

**[0066]** In the context of the present disclosure, the steam quality of the steam-enhanced steam is “enhanced” (*i.e.* boosted) in that it has a greater steam quality than it would be but for the contribution of the auxiliary-vapour stream. In select embodiments of the present disclosure, at the second pressure condition and the second temperature condition, the vapour-enhanced stream has a steam quality of at least about 3 % (preferably between about 10 % and about 20 %) to substantially prevent nucleate boiling during the heating of the steam-enhanced stream. In the context of the present disclosure, steam quality is the mass fraction of vapor.

**[0067]** In select embodiments of the present disclosure, the steam quality required to substantially prevent nucleate boiling may be determined, for example, by using the boiling index, the boiling number, the Lockhart-Martinelli correlation, the Chen correlation, or a combination thereof.



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The boiling index may be as shown in **EQN. 4**

$$B_i = B_o * X \qquad \textbf{EQN. 4}$$

wherein: $B_i$ is the boiling index (dimensionless); $B_o$ is the boiling number; and $X$ is the Lockhart-Martinelli parameter.

**[0068]** The boiling number, $B_o$, may be as shown in **EQN. 5**

$$B_0 = \mathrm{q}/(\mathrm{G}\mathrm{h}_{fg}) \qquad \textbf{EQN. 5}$$

wherein: $q$ is the heat flux (in W/m$^2$); $\mathrm{G}$ is the mass flux (*i.e.* the mass rate divided by the flowing cross sectional area of the tube) of the two phase system (in kg/m$^2$/s); and $\mathrm{h}_{fg}$ is the evaporative enthalpy (*i.e.* the difference in enthalpy between saturated vapor and saturated liquid at the pressure or temperature owing condition) (in J/kg).

**[0069]** The Lockhart-Martinelli number for turbulent/turbulent flow regime can be estimated by the correlation shown in **EQN. 6**.

$$X_{tt} = \left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1} \qquad \textbf{EQN. 6}$$

Wherein: $\mathrm{X_{tt}}$is the Lockhart-Martinelli number for the turbulent-turbulent flow regime; $\mathrm{x}$ is the steam quality, $\mu_G$ and $\mu_L$ are the vapour and liquid phase dynamic viscosity, respectively (in Pa·s); and $\rho_G$ and $\rho_L$ are the vapour and liquid density, respectively (in kg/m$^3$).

**[0070]** **EQN. 6** indicates that, for a given boiler operating condition, the Lockhart-Martinelli number is large at low steam qualities (*i.e.* as $\mathrm{x}$ approaches zero) and decreases as the steam quality increases (*i.e.* as 1-$\mathrm{x}$ approaches zero). This causes the boiling index to decrease with an increase in steam quality. At high boiling index numbers (low steam qualities), nucleate boiling is the dominant heat transfer mechanism. At low boiling index numbers (high steam qualities), forced convective evaporation is the dominant heat transfer mechanism. A typical criterion for the transition from nucleate boiling to convective evaporation is in the range of about $B_i < 0.00010$ to $B_i < 0.00025$.

**[0071]** Select embodiments of the present disclosure comprise heating the vapour-enhanced stream to increase the steam quality thereof. The heating of the vapour-enhanced stream may occur primarily by radiative heating, for example in a radiant-heating



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section of steam generator; or primarily convective heating, for example in a section of the economizer, which is a combination of convective and radiant heat transfer from the flue gases, with the radiant component decreasing as the flue gas temperature decreases; or by some combination of thereof. In the context of the present disclosure, "radiant-heating section" refers to the section in a steam generator where the heating of the vapour-enhanced stream is primarily achieved by radiant heat transfer.

**[0072]** In select embodiments of the present disclosure, the heating of the vapour-enhanced stream may comprise providing an average heat flux of between about 50 $kW/m^2$ and about 160 $kW/m^2$ (on an inside area basis), and a peak heat flux of between about 150 $kW/m^2$ and 300 $kW/m^2$ (on an inside area basis). After heating the vapour-enhanced stream, the steam-enhanced stream may have a steam quality of between about 70 % and about 100 %.

**[0073]** Select embodiments of the present disclosure comprise injecting at least a portion of the steam-enhanced stream into a hydrocarbon-containing reservoir. In the context of the present disclosure, a reservoir is a subsurface formation containing one or more natural accumulations of moveable petroleum, which are generally confined by relatively impermeable rock. An “oil sand” or “oil sands” reservoir is generally comprised of strata of sand or sandstone containing petroleum. In the context of the present disclosure, petroleum is a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid, or solid phase. In the context of the present disclosure, the words “petroleum” and “hydrocarbon(s)” are used to refer to mixtures of widely varying composition. The production of petroleum from a reservoir necessarily involves the production of hydrocarbons but is not limited to hydrocarbon production and may include, for example, trace quantities of metals (*e.g.* Fe, Ni, Cu, V). Similarly, processes that produce hydrocarbons from a well will generally also produce petroleum fluids that are not hydrocarbons. In accordance with this usage, a process for producing petroleum or hydrocarbons is not necessarily a process that produces exclusively petroleum or hydrocarbons, respectively. In the context of the present disclosure, “fluids”, such as petroleum fluids, include both liquids and gases. It is common practice to categorize petroleum substances of high viscosity and density into two categories, “heavy oil” and “bitumen”. For example, some sources define “heavy oil” as a petroleum that has a mass density of greater than about 900 $kg/m^3$. Bitumen is sometimes described as that portion of petroleum that exists in the semi-solid or solid phase in natural deposits, with a mass



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density greater than about 1,000 kg/m$^3$ and a viscosity greater than 10,000 centipoise (cP; or 10 Pa·s) measured at original temperature in the deposit and atmospheric pressure, on a gas-free basis. Although these terms are in common use, references to heavy oil and bitumen represent categories of convenience, and there is a continuum of properties between heavy oil and bitumen. Accordingly, references to heavy oil and/or bitumen herein include the continuum of such substances, and do not imply the existence of some fixed and universally recognized boundary between the two substances. In particular, the term “heavy oil” includes within its scope all “bitumen” including hydrocarbons that are present in semi-solid or solid form.

**[0074]** In select embodiments of the present disclosure, at least a portion of the steam-enhanced stream is injected into the reservoir to facilitate thermal recovery. “Thermal recovery” or “thermal stimulation” refers to enhanced oil recovery techniques that involve delivering thermal energy to a petroleum resource, for example to a heavy oil reservoir. There are a significant number of thermal recovery techniques other than SAGD, such as cyclic steam stimulation (CSS), solvent-aided processes (SAP), solvent-driven processes (SDP), in-situ combustion, hot water flooding, steam flooding, and electrical heating. In general, thermal energy is provided to reduce the viscosity of the petroleum to facilitate production. This thermal energy may be provided by a “thermal recovery fluid”, which is a fluid that carries thermal energy, for example in the form of steam, solvents, or mixtures thereof (with or without additives such as surfactants).

**[0075]** In select embodiments of the present disclosure, a portion of the steam-enhanced stream may be recycled to form the auxiliary-vapour stream. For example, between about 3 % and about 30 % (preferably between about 5 % and about 20 %) by weight of the steam-enhanced stream may be recycled to form the auxiliary-vapour stream. Alternatively, the auxiliary-vapour stream may be provided from an auxiliary steam-generation system. The auxiliary steam-generation system may be substantially smaller in scale than the primary steam-generation system, and it may be configured to optimize the relevant parameters of the auxiliary-vapour stream (such as steam quality, inlet pressure, and/or temperature). Such optimizations are within the purview of those skilled in the art having benefited from the teachings of the present disclosure. The auxiliary-vapour generation system may be configured to generate the auxiliary-vapour stream from a source that is not derived from a produced fluid or from a source that is derived from a produced fluid but that has been treated.



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**[0076]** Select embodiments of the present disclosure may further comprise separating the steam-enhanced stream into a substantially vapor-phase stream and a substantially liquid-phase stream prior to injection into the hydrocarbon-containing reservoir. For example, the steam-enhanced stream may be separated such that the substantially vapor-phase stream accounts for between about 70 % and about 95 % (preferably between about 80 % and about 90 %) of the steam-enhanced stream, and the substantially liquid-phase stream may account for between about 30 % and about 5 % (preferably between about 20 % and about 10 %) by weight of the steam-enhanced stream. The liquid-phase stream may for example be treated to provide a feedwater, or directed to disposal or an alternative use. A portion of the substantially vapor-phase stream may be recycled to form the auxiliary-vapour stream. For example, between about 3 % and about 30 % by weight of the substantially vapor-phase stream may be recycled to form the auxiliary-vapour stream.

**[0077]** In select embodiments of the present disclosure, the separating of the steam-enhanced stream into the substantially vapor-phase stream and the substantially liquid-phase stream may occur in a separator. The separator may be, for example, a flash vessel. In the context of the present disclosure, a flash vessel is one which is configured to separate steam from condensate. In a typical flash vessel, condensate and steam enter as a two-phase mixture, and the condensate is separated by gravity or centrifugal forces and collected from the base of the vessel while the steam is collected from the top of the vessel after possibly passing through a device to further remove entrained condensate droplets. In the context of the present disclosure, the collected condensate may be recycled into the feedwater stream, for example upstream of the pressurizing element, or simply disposed. The collected steam in the vessel is piped from the top of the vessel to any appropriate pressure steam equipment or routed directly into the wellbore.

**[0078]** **FIG. 1** is a schematic diagram showing variations in the bulk temperature 100 ($T_b$) and wall temperature 102 ($T_w$) as water is heated through a boiler tube 104. In **FIG. 1**, schematic points in the heat transfer mechanism are indicated with reference numbers 106-120.

**[0079]** Between point 106 and 108, $T_w$ is lower than the saturation temperature ($T_s$). Therefore, ordinary convective heat transfer is likely to occur between the wall and the liquid in this zone. The same is observed between point 108 and point 110, where the wall superheat, ($\Delta T$ = $T_w - T_s$), is insufficient to activate nucleation centers. The first vapor



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bubbles appear on the wall at point 110. The degree of the wall overheating needed for incipient boiling depends on the thermo-physical properties of the fluid, tube geometry, local values of heat flux, mass velocity, and the quantity of subcooling. Despite overheating of the liquid layers near the hot wall, the bulk flow temperature at point 110 remains lower than $T_s$. As a result, so-called "surface boiling" or "subcooled boiling" may be observed. In this region, bubbles may form on the wall and condense into the bulk fluid.

**[0080]** In **FIG. 1**, The subcooled boiling zone extends up to point 112 where $T_s = T_b$ and the steam quality is zero (*i.e.* $x$ = 0). At point 112, $x = (h - h_L)/h_{LG}$, where *h* is the bulk enthalpy of the fluid, $h_L$ the saturated liquid enthalpy on the saturation line, and $h_{LG}$ is the latent heat of vaporization. The zone of saturated nucleate boiling follows point 112, when $T_s = T_b$ and $x > 0$. Initially, the vapor bubbles in subcooled boiling (between point 110 and point 112) may not break away from the wall or slip along it. Before the condition of net vapor generation (point 112), bubbles may leave the wall and may condense in the flow of subcooled liquid. After this point, an ever increasing quantity of vapor accumulates in the flow core.

**[0081]** In the neighborhood of point 114, the fraction of the channel cross section occupied by vapor is relatively large, and annular flow arises with the liquid film flowing on the channel wall and a vapor core occupying in the center. Within this regime nucleate boiling is suppressed (point 116). As the vapor-liquid mixture continues to flow, the quantity of liquid on the wall decreases and, at a certain boundary vapor quality (point 118), dry out occurs. In other words, at point 118 there may no longer be any liquid-to-heat-transfer-surface contact, and the wall temperature may rise. A transition occurs to dispersed, or the fog-type, flow of the mixture between point 118 and 120 with a maximum occurring at point 122. After point 120, the entire flow stream is vaporized, and the steam is superheated by ordinary convective heat transfer.

**[0082]** As will be appreciated by those skilled in the art having benefited from the teachings of the present disclosure, while points 106-120 generally indicate various instances within a simplified mechanism of heat transfer, steam generation mechanisms are complex and often occur in concert. Accordingly, more quantitative analyses may be required to differentiate the mechanism(s) of heat transfer for a given system (such as set out herein with respect to **EQN. 1** – **EQN. 6**).



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**[0083]** **FIG. 2** provides a schematic of a system for generating steam for a thermal recovery process for hydrocarbon production in accordance with select embodiments of the present disclosure. In the system of **FIG. 2**, a steam generator 200 comprises a pressurizing element 202, an economizer section 204, an eductor 206, a radiant section 208, and a separator 210. The pressurizing element 202 is configured to pressurize a feedwater stream 212. After pressurization, the feedwater stream 212 enters the economizer section 204 which is configured to pre-heat the feedwater stream 212 (such as by heat exchange with exhausted boiler gases). Because of the elevated pressure of the feedwater stream 212 in the economizer section 204, the feedwater stream 212 is not substantially vaporized at this point. Instead, in select embodiments, the feedwater stream 212 remains substantially or entirely in the liquid phase in the economizer section 204. After pre-heating in the economizer section 204, the feedwater stream 212 passes through the eductor 206. Within the eductor 206, the feedwater stream 212 acts as a motive fluid in that it draws an auxiliary-vapour stream 214 into the eductor 206 to mix with feedwater stream 212 thereby forming a vapour-enhanced stream 216 (in which the vapour may for example be steam or another gas). As such, the eductor functions as a stream connector. The addition of the auxiliary-vapour stream 214 to the feedwater stream 212 is carried out so that that steam quality of the vapour-enhanced stream 216 is sufficient to mitigate nucleate boiling during heating in the radiant section 208. The eductor may also reduce the pressure of the feedwater stream 212 such that at least a portion of the feedwater stream 212 is vaporized to steam. The pressure drop at the eductor 206 is lower than would be required to attain the desired steam quality absent the addition of the auxiliary-vapour stream 214. In the radiant section 208, the vapour-enhanced stream 216 is heated to generate steam of a specified quality. The separator 210 is configured to separate a high-quality steam stream 218 from a low-quality steam stream 220. The high-quality steam stream 218 is suitable for injection downhole in a thermal recovery process such as a SAGD process. A first portion of the high-quality steam stream 218 is recycled back to the eductor 206 as the auxiliary-vapour stream 214 (such that the auxiliary-vapour stream is a recycled-steam stream). A second portion of the high-quality steam stream 218 is supplied to the thermal recovery operation. The low-quality steam stream 220 contains the majority of the unvaporized/condensate water from the feedwater stream 212, and it may be recycled into the feedwater stream 212 (for example upstream of the pressurizing element 202) or discharged from the steam generator 200.



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**[0084]** **FIG. 3A** provides a schematic of an eductor 300 which may be utilized in accordance with select embodiments of the present disclosure. The eductor comprises a motive-fluid inlet 302, a suction inlet 304, a nozzle 306, a diffuser 308, and an outlet 310. With reference to the schematic of **FIG. 2**, the eductor 300 may be configured such that the motive-fluid inlet 302 receives the feedwater stream 212, the suction inlet 304 receives the auxiliary-vapour stream 214, and the outlet 310 discharges the steam-enhanced stream 216.

**[0085]** A thermodynamic balance around the educator 300 may be performed to estimate its ideal performance. Ideal performance for compressors generally assume a reversible process (*i.e.* there is no change in entropy) and the shaft work put into the fluid acts on the fluid isentropically. For jet compressors (such as the eductor 300), there is no shaft work, and the device can be assumed to be adiabatic (*i.e.* there is no change in overall enthalpy as the heat loss can be ignored). The specific enthalpy and entropy for water and steam is known for the normal range of operating conditions. In the present example, the pressures and temperatures are known for the feedwater stream 212 and the auxiliary-vapour stream 214. The ideal operating pressure at outlet 310 and the flowrate of stream 212 into the motive-fluid inlet 302 are also known. As such, in the present example, the sole unknown variable is the flowrate of the auxiliary-vapour stream 214 into the suction inlet 304. By modeling a series of flow rates for auxiliary-vapour stream 214, the resulting discharge steam quality can be attained from the enthalpy balance. Knowing the discharge enthalpy, the discharge entropy is also known, and the recycle stream rate can be adjusted to balance the overall entropy. The theoretical recycle steam rate can be determined for a multitude of motive fluid conditions, and outlet pressures, and the real rate will be some fraction of the ideal rate.

**[0086]** By way of example, for a 325 °C target jet pump discharge, and a 310 °C steam saturation recycle supply, estimated ideal discharge parameters from the eductor 300 (discharge pressures and degrees of subcool) are shown in **FIG. 3B**, and the related quantity of the auxiliary-vapour stream, relative to the feedwater stream inlet flow rate is shown in **FIG 3C.** In **FIG. 3B**, reference numbers 320, 322, 324, 326, 328, 330, 332, 334, 336, and 338, indicate trends for 0 °C, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, and 45 °C subcool, respectively. In **FIG. 3C**, reference numbers 350, 352, 354, 356, 358, 360, 362, 364, 366, and 368, indicate trends for 0 °C, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, and 45 °C subcool, respectively.



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**[0087]** As will be appreciated by those skilled in the art having benefited from the teachings of the present disclosure, flash steam generation across a pressure drop at the eductor 300 reduces the quantity of auxiliary-vapour required to provide a particular steam quality for the vapour-enhanced stream. In the absence of any contribution from the auxiliary-vapour stream, the quantity of (simple) flash steam created by reducing the feedwater stream pressure to the steam-enhanced stream is shown in **FIG 3D.** In **FIG. 3D**, reference numbers 380, 382, 384, 386, 388, 390, and 392 indicate trends for 0 °C, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, and 30 °C subcool, respectively.

**[0088]** As indicated in **FIG. 3D,** In the present example, operating the feedwater stream inlet at 16 MPa and 20 °C subcool, provides a steam quality of about 0.41 % steam quality under simple flash conditions (to the eductor discharge conditions at outlet 310). At 100 % efficiency, the eductor 300 draws in approximately 16.6 tonne of 310 °C auxiliary-vapour stream per 100 tonne of feedwater stream, and discharges the enhanced-steam stream at 15 % steam quality at 325 °C saturation temperature. In the present example a 60 % efficiency rating for the eductor 300 equates to approximately 10 tonne of 310 °C saturated steam per 100 tonne of feedwater stream being drawn in, resulting in a discharge of 9.8 % steam quality at 325 °C saturation temperature.

**[0089]** In the present example, a higher motive inlet pressure is needed to increase the steam quality at the discharge condition. Operating at 17 MPa and 25 °C subcool, equates to approximately 0.17% steam quality generated by the simple flash to the eductor discharge conditions. At 100 % jet pump efficiency, the eductor draws in approximately 20.7 tonne of 310 °C saturated steam per 100 tonne of feedwater, and discharges 17.9 % steam quality at 325 °C saturation temperature. Assuming that a 60 % efficiency is maintained, approximately 12.4 tonne of 310 °C saturated steam per 100 tonne of feedwater would be drawn in, resulting in a discharge of 11.6 % steam quality at 325 °C saturation temperature.

**[0090]** Operating with less subcool in advance of the eductor 300 may be beneficial, as the resulting flash steam reduces the amount of auxiliary steam needed to attain a target discharge steam quality. For the above examples, operating with 10 °C less subcool (i.e. 10 °C and 15 °C subcool for 16 MPa and 17 MPa, respectively), results in a discharge steam quality (with 60 % eductor efficiency) of 16.2 % steam quality and 17.7 % steam quality (from 9.8% and 11.6%). The simple flash from the eductor outlet conditions results in 6.21 % and 5.84% steam quality, respectively (from 0.41% and 0.17%).



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**[0091]** Conversely, operating with more subcool in advance of the eductor is not ideal, as auxiliary steam is required to provide heat to the motive fluid. For the above two examples, operating with 10 °C more subcool (i.e. 30 °C and 35 °C subcool for 16 MPa and 17 MPa respectively), results in a discharge steam quality (with 60% eductor efficiency) of 5.4% steam quality and 7.4% steam quality (from 9.8 % and 11.6%). The simple flash from the eductor outlet conditions results in 8.8 °C and 9.1 °C subcool, respectively (from 0.41 % and 0.17 % steam quality.

**[0092]** **FIG. 4** provides a plot 400 of heat flux at the onset of nucleate boiling (ONB) as a function of the difference between the local fluid temperature and the local saturation temperature (*i.e.* the degree of subcool) for a series of different saturation temperatures and fluid flow rates as set out in Table 1 (functions 402, 404, 406, 408, and 410). Such functions provide a means to determine the conditions associated with the onset of nucleate boiling for a given set of conditions. The plot 400 in **FIG. 4** is based on a steam generation rate of about 167 T/hr from a six-coil steam generation unit (nominal pipe size = 3"; schedule 80), where each coil provides a flow of about 27,833 kg/hr. The steam generator comprises a pressurizing element, an economizer section, an eductor, a radiant section, and a separator as shown schematically in **FIG. 2**. The eductor is configured substantially as shown schematically in **FIG. 3**.

**[0093]** Table 1: Saturation temperatures and flow rates for a series of functions as shown in plot 400 of **FIG.** 4

| **Reference number** | **Saturation temperature (°C)** | **Fluid flow rate (%)** |
|---|---|---|
| 402 | 360 | 100 |
| 404 | 340 | 100 |
| 406 | 320 | 100 |
| 408 | 100 | 100 |
| 410 | 100 | 10 |



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**[0094]** For each of the functions 402, 404, 406, 408, and 410, heat flux values were calculated using the film properties of the water (*i.e.* the arithmetic average of the fluid and the inside heat transfer surface temperature), the Dittus-Boelter formula and the temperature difference between the bulk fluid temperature and the temperature at the inside of the heat transfer surface.

**[0095]** Similarly, for each of the functions 402, 404, 406, 408, and 410 the nucleate boiling heat transfer coefficient (at the onset of nucleate boiling) was estimated using the Burgles-Rohsenow nucleation criteria. Functions 402, 404, 406, 408, and 410 are archetypal, and those skilled in the art having benefitted from the teachings of the present disclosure will appreciate how to generate alternative functions to account for the specific conditions associated with a particular steam generation system.

**[0096]** The plot 400 in **FIG. 4** indicates that greater extents of subcooling are required to prevent nucleate boiling at increasing heat flux rates. Put another way, for a given heat flux, more subcool is needed as the saturation temperature (and the coincident operating pressure) is reduced. The plot in **FIG. 4** also indicates that significantly more subcool is needed at low flow rates (see, for example, function 408 vs. function 410).

**[0097]** Using the function 406 as an example, for a boiler providing a peak heat flux of 300,000 W/m$^2$ the plot of **FIG. 4** indicates that the onset of nucleate boiling occurs at about 20 °C. Accordingly, in the first stage of the steam generation method, operational parameters may be set to ensure the subcool is greater than about 22 °C such that the heat flux is not sufficient to induce nucleate boiling.

**[0098]** **FIG. 5** provides a plot 500 of heat flux as a function steam quality at the transition out of the nucleate boiling regime for a series of different saturation temperatures and fluid flow rates as set out in Table 2 (functions 502, 504, and 506). Such functions provide a means to determine the steam quality required to ensure that the heat transfer mechanism in the radiant-heating section of the steam generator is predominantly forced convective evaporation rather than saturated nucleate boiling.



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**[0099]** Table 2: Saturation temperatures and flow rates for a series of functions as shown in plot 500 of **FIG. 5**

| **Reference number** | **Saturation temperature (°C)** | **Fluid flow rate (%)** |
|---|---|---|
| 502 | 310 | 100 |
| 504 | 320 | 100 |
| 506 | 320 | 80 |

**[00100]** The plot 500 in **FIG. 5** indicates that higher steam quality is needed at higher heat flux to ensure that heating is predominantly by the forced convective evaporative mechanism and not occurring with the saturated nucleate boiling mechanism. The plot 500 in **FIG. 5** also indicates that at lower pressures (for a given heat flux) less steam quality is needed to ensure that heating is predominantly by the forced convective evaporative mechanism and not by the saturated nucleate boiling mechanism (see, for example, function 502 vs. function 504). The plot in **FIG. 5** also indicates that at lower flow rates (for a given heat flux) more steam quality is needed to ensure that heating is predominantly by the forced convective evaporative mechanism and not by the saturated nucleate boiling mechanism (see, for example, function 504 *vs.* function 506).

**[00101]** Using the function 504 as an example and assuming a peak heat flux of about 160,000 W/m$^2$ in the radiant-heating section, the plot of **FIG. 5** indicates that a steam quality of at least about 12 % steam quality is necessary to ensure is that heat transfer is predominantly by the forced convective evaporative mechanism and not by the saturated nucleate boiling mechanism. . This finding, in combination with that from the first stage, suggests that a suitable system/method for generating steam in accordance with the present disclosure may comprise configuring the operational parameters of the first stage to ensure a subcool of at least about 22 °C and configuring the operational parameters of the second stage to ensure a steam quality of at least about 12 %. Based on these parameters, an ideal system/method may be designed (*i.e.* a 100 % efficient system/method) by balancing the thermodynamic aspects of the eductor using an isentropic and isenthalpic analysis. For example, performing calculations based on a discharge pressure of 11,000 kPa (which may drop to about 9,800 kPa) due to hydraulic loss up to



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the separator) and an auxiliary-vapour stream having a saturation temperature of about 310 °C, varying the saturation temperature and subcool of the motive fluid (*i.e.* the feedwater stream) provides the results set out in Table 3.

**[00102]** Table 3: Operational parameters for a steam generation system based on an isentropic and isenthalpic analysis of an eductor having 100% efficiency

| **Entry** | **Saturation pressure (kPa)** | **Saturation temp. (°C)** | **Subcool (°C)** | **Steam quality without enhancement from auxiliary steam stream (%)** | **Weight percent recycled steam in the steam enhanced stream (%)** | **Outlet steam quality (%)** |
|---|---|---|---|---|---|---|
| 1 | 12,762 | 330.0 | 0 | 5.72 | 35.83 | 40.17 |
| 2 | 12,762 | 330.0 | 5 | 2.94 | 11.74 | 14.56 |
| 3 | 12,762 | 330.0 | 10 | 0.33 | 10.98 | 11.47 |
| 4 | 12,762 | 330.0 | 15 | 4.27 | 11.22 | 9.50 |
| 5 | 12,762 | 330.0 | 20 | 9.19* | 12.38 | 8.61 |
| 6 | 12,762 | 330.0 | 25 | 14.12* | 14.35 | 8.73 |
| 7 | 12,762 | 330.0 | 30 | 19.06* | 17.00 | 9.74 |
| 8 | 12,762 | 330.0 | 35 | 24.00* | 20.18 | 11.51 |
| | | | | | | |
| 9 | 14,504 | 340.0 | 0 | 11.21 | 27.05 | 35.73 |
| 10 | 14,504 | 340.0 | 5 | 8.10 | 23.93 | 30.54 |
| 11 | 14,504 | 340.0 | 10 | 5.25 | 21.65 | 26.17 |
| 12 | 14,504 | 340.0 | 15 | 2.57 | 20.22 | 22.65 |
| **13** | **14,504** | **340.0** | **20** | **0.03** | **19.61** | **20.00** |
| 14 | 14,504 | 340.0 | 25 | 4.76* | 19.80 | 18.24 |
| 15 | 14,504 | 340.0 | 30 | 9.60* | 20.73 | 17.35 |
| 16 | 14,504 | 340.0 | 35 | 14.47* | 22.33 | 17.27 |
| | | | | | | |
| 17 | 15,444 | 345.0 | 0 | 14.17 | 33.70 | 43.73 |
| 18 | 15,444 | 345.0 | 5 | 10.82 | 30.17 | 38.29 |
| 19 | 15,444 | 345.0 | 10 | 7.81 | 27.42 | 33.60 |
| 20 | 15,444 | 345.0 | 15 | 5.02 | 25.40 | 29.62 |
| 21 | 15,444 | 345.0 | 20 | 2.39 | 24.12 | 26.39 |
| 22 | 15,444 | 345.0 | 25 | 0.23 | 23.58 | 23.99 |
| 23 | 15,444 | 345.0 | 30 | 5.00* | 23.75 | 22.27 |
| 24 | 15,444 | 345.0 | 35 | 9.81* | 24.59 | 21.38 |
| | | | | | | |
| 25 | 16,433 | 350.0 | 0 | 17.33 | 40.13 | 51.26 |
| 26 | 16,433 | 350.0 | 5 | 13.65 | 36.29 | 45.67 |
| 27 | 16,433 | 350.0 | 10 | 10.44 | 33.20 | 40.80 |
| 28 | 16,433 | 350.0 | 15 | 7.52 | 30.76 | 36.55 |
| 29 | 16,433 | 350.0 | 20 | 4.80 | 28.97 | 32.92 |



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| | | | | | | |
|---|---|---|---|---|---|---|
| 30 | 16,433 | 350.0 | 25 | 2.21 | 27.83 | 29.95 |
| 31 | 16,433 | 350.0 | 30 | 0.51 | 27.35 | 27.67 |
| 32 | 16,433 | 350.0 | 35 | 5.24* | 27.50 | 26.09 |
| | | | | | | |
| 33 | 17,474 | 355.0 | 0 | 20.75 | 46.26 | 58.28 |
| 34 | 17,474 | 355.0 | 5 | 16.61 | 42.16 | 52.56 |
| 35 | 17,474 | 355.0 | 10 | 13.16 | 38.84 | 47.62 |
| 36 | 17,474 | 355.0 | 15 | 10.09 | 36.12 | 43.24 |
| 37 | 17,474 | 355.0 | 20 | 7.25 | 33.95 | 39.38 |
| 38 | 17,474 | 355.0 | 25 | 4.58 | 32.36 | 36.06 |
| 39 | 17,474 | 355.0 | 30 | 2.03 | 31.34 | 33.33 |
| 40 | 17,474 | 355.0 | 35 | 0.79 | 31.34 | 31.65 |
| | | | | | | |
| 41 | 18,570 | 360.0 | 0 | 24.57 | 52.11 | 64.86 |
| 42 | 18,570 | 360.0 | 5 | 19.73 | 47.67 | 58.89 |
| 43 | 18,570 | 360.0 | 10 | 15.98 | 47.67 | 56.93 |
| 44 | 18,570 | 360.0 | 15 | 12.72 | 41.34 | 49.58 |
| **45** | **18,570** | **360.0** | **20** | **9.75** | **38.93** | **45.62** |
| 46 | 18,570 | 360.0 | 25 | 6.98 | 37.01 | 42.10 |
| 47 | 18,570 | 360.0 | 30 | 4.36 | 35.59 | 39.06 |
| 48 | 18,570 | 360.0 | 35 | 0.02 | 34.68 | 36.55 |

Note: * indicates that the outlet is liquid phase only. Values are the degrees of subcool in °C.

**[00103]** In Table 3, entry 13 indicates that the 20 °C subcool required to prevent nucleate boiling in the first stage provides a steam quality of only 0.03 % which is at least about 11.7 % below that required to prevent nucleate boiling in the second stage. However, under the conditions of entry 13, the auxiliary-vapour stream provides an additional 19.61 % to the steam quality. This enhancement to the steam quality at the second stage ensures the steam quality is sufficient to mitigate nucleate boiling in the radiative-heating section of the steam generator.

**[00104]** More generally, those skilled in the art having benefited from the teachings of the present disclosure will recognize that that high pressures are needed to maintain the system in the preferred operating range in the absence of the auxiliary-vapour stream in the present context and under the majority of typical operating conditions employed in the field. For example at 18,570 kPa and 20 °C subcool, flashing in the absence of the enhancement from the auxiliary-vapour stream produces a steam quality of only about 9.75% (entry 45 of Table 3). By adding heat via the auxiliary-vapour stream, the methods and systems of the present disclosure address this shortcoming and provide improved operational efficiency with systems and methods that are readily employable under the typical operating conditions employed in the field.



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**[00105]** As noted above, finned tubes may be configured to facilitate the methods of the present disclosure. **FIG. 6** shows a scatter plot of typical normal peak operating heat flux values based on the external surface area throughout a typical boiler or HRSG. In **FIG. 6**, reference numbers 600, 602, and 604 identify 9-path, 12-path, and 16-path configurations, respectively. By selecting different finned configurations, the resulting peak heat flux (based on inside area) can be estimated as shown in **FIG. 7** which provides a scatter plot of peak heat flux values on an inside area basis. In **FIG. 7**, 9-path, 12-path, and 16-path configurations are plotted. For example, a flue gas temperature between about 900 °C and about 1000 °C, correlates to a heat flux is of between about 25 kW/m$^2$ to 30 kW/m$^2$ of external surface area. Fins may be selected to effectively concentrate the heat flux at the external surface to the internal surface, where the boiling takes place, by a multiplier as exemplified in Table 4.

**[00106]** Table 4: Operational parameters and fin configurations for considering external and internal heat flux

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fin Height | ins | - | 0.375 | 0.500 | 0.625 | 0.750 | 1.000 |
| Fin spacing | qty/inch | - | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 |
| Ratio (total outside area to pipe inside area, NPS 3 S160) | Ao/Ai | 1.33 | 6.96 | 9.07 | 11.30 | 13.65 | 18.71 |
| Ratio (total outside area to pipe inside area, NPS 3 S80) | Ao/Ai | 1.21 | 6.30 | 8.21 | 10.23 | 12.35 | 16.93 |

**[00107]** In the present example, a fin height of 12.7 mm (1/2 inch) and a fin density (i.e. fin quantity per unit length) of 197 fins/meter (5 fins per inch) would likely be suitable in that it would yield a 9.07 external to internal area ratio for NPS 3 S160 pipe, thereby resulting in a heat flux of between about 225 kW/m$^2$ and about 275 kW/m$^2$ based on inside surface area.

**[00108]** Those skilled in the art having benefit from the teaching of the present disclosure will recognize how to select the fin profile and density to maximize the peak heat flux within the allowable temperature limits of the selected fin and tubing material thereby minimizing the coil length. By selecting appropriate fin profiles throughout the economizer, the peak heat flux may be controlled to a level commensurate with the amount of subcool available (to prevent subcooled boiling) and with the available capacity of the auxiliary-vapour stream (to have sufficient velocity to ensure that forced convective evaporation mechanism dominates over the saturated nucleate boiling heat transfer mechanism). In the present example, the approximate peak heat flux based on internal area for bare tubes may be between about 30 kW/m$^2$ and about 40 kW/m$^2$, indicating that, with the wide availability of fin profiles and density, a peak heat flux between about 30 kW/m$^2$ and about 275 kW/m$^2$



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may be attained with a flue gas temperature of 900 °C to 1000 °C (a typical flue gas temperature leaving the shock tube section).

**[00109]** **FIG. 8** shows a scatter plot of typical normal peak operating heat flux values based on the external surface area for radiant and shock tube components of typical boiler or HRSG. In **FIG.** 8, reference numbers 800, 802, 804, 806, 808, and 810 identify 9-path shock, 12-path shock,16-path shock, 9-path radiant, 12-path radiant, and 16-path radiant configurations, respectively. **FIG.** 9 provides a scatter plot of peak heat flux values for the same configurations on an inside area basis. In **FIG. 9**, reference numbers 900, 902, 904, 906, 908, and 910 identify 9-path shock, 12-path shock,16-path shock, 9-path radiant, 12-path radiant, and 16-path radiant configurations, respectively. For the shock tube and radiant sections, there may be less flexibility in managing the peak heat flux, as the bare tube peak heat flux is relatively high. For example, as shown **FIG. 8**, 975 °C to 1300 °C flue gas temperatures correspond to between about 150 kW/m$^2$ and about 290 kW/m$^2$ due to the radiant contribution to the external heat transfer mechanism. As will be appreciated by those skilled in the art having benefited from the teachings of the present disclosure, this may limit the outlet kinetic energy to within a prescribed value. In the present example, the kinetic energy may be determined by the product of the density (in kg/m$^3$ or lb/ft$^3$) and the square of the velocity (in m/s or ft/s) and may be limited to a value of approximately 4839 kg·m/s$^2$ (35,000 ft·lb/s$^2$). This may be determined at the outlet condition of the coil, at the intended steam quality (typically 85 %) and intended outlet operating pressure. As the typical steam generator is a continuous coil from inlet to outlet, this then defines the mass rate for the individual coil. Setting a normal design envelope of 70% to 110 % of the maximum recommended value, this corresponds to a mass flux rate between about1317 kg/m$^2$/s and about 2069 kg/m$^2$/s for 10 MPa operation, and between about 895 kg/m$^2$/s and about 1407 kg/m$^2$/s for 5 MPa operation. The amount of subcool necessary to prevent the onset of nucleate boiling is primarily a function of the mass flux rate, the heat flux rate, the operating pressure, and slightly influenced with the coil diameter. The relationship for NPS 3 S160 pipe coil is shown in the **FIG. 10** and **FIG. 11**.

**[00110]** In **FIG. 10**, reference numbers 1000, 1002, 1004, 1006, and 1008 represent 6 MPa, 9 MPa, 12 MPa, 15 MPa, and 18 MPa, respectively (at 2069 kg/m$^2$/s). In **FIG.** 11, reference numbers 1100, 1102, 1104, 1106 and 1108 represent 6 MPa, 9 MPa, 12 MPa, 15 MPa, and 18 MPa, respectively (at 895 kg/m$^2$/s). Specific parameters for a selection of operating points from **FIG. 10** and **FIG. 11** are provided in Table 5.



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**[00111]** Table 5: Specific parameters for a selection of operating points from **FIG.** 10 and **FIG.** 11.

| Fraction of design rate | 110% | | 100% | | 70% | |
|---|---|---|---|---|---|---|
| Mass Flux | 2069 kg/m2/s | | 1881 kg/m2/s | | 895 kg/m2/s | |
| Operating Pressure | 18 MPa | 6 MPa | 18 MPa | 6 MPa | 18 MPa | 6 MPa |
| Subcool req'd at 100 kW/m2 | 4.5 °C | 5.8 °C | 4.9 °C | 6.3 °C | 9.5 °C | 11.8 °C |
| Subcool req'd at 200 kW/m2 | 9.6 °C | 11.9 °C | 10.5 °C | 12.9 °C | 20.4 °C | 24.1 °C |
| Subcool req'd at 300 kW/m2 | 15.0 °C | 18.0 °C | 16.4 °C | 19.6 °C | 31.9 °C | 36.7 °C |

**[00112]** As noted above, the steam quality necessary to provide sufficient superficial velocity to ensure that the predominant heat transfer mechanism is forced convective evaporation is primarily a function of the mass flux rate, the heat flux rate, and the operating pressure. In the present example, this is shown in **FIG. 12** and **FIG. 13**. In **FIG. 12**, reference numbers 1200, 1202, and 1204 represent 10 MPa 2069 kg/m$^2$/s, 7.5 MPa 1752 kg/m$^2$/s, and 5 MPa 1407 kg/m$^2$/s, respectively. In **FIG. 13**, reference numbers 1300, 1302, and 1304 represent 10 MPa 1317 kg/m$^2$/s, 7.5 MPa 1114 kg/m$^2$/s, and 5 MPa 895 kg/m$^2$/s, respectively. Table 6 provides bracketing ranges for some of the operating conditions characterized in **FIG. 12** and **FIG. 13**.

**[00113]** Table 6: Bracketing ranges for some of the operating conditions characterized in **FIG. 12** and **FIG. 13**

| Fraction of design rate | 110% | | 100% | | 70% | |
|---|---|---|---|---|---|---|
| Operating Pressure | 10 MPa | 5 MPa | 10 MPa | 5 MPa | 10 MPa | 5 MPa |
| Mass Flux (kg/m2/s) | 2069 | 1407 | 1881 | 1279 | 1317 | 895 |
| SQ req'd at 100 kW/m2 | 5.7% | 4.4% | 6.3% | 4.8% | 9.1% | 7.0% |
| SQ req'd at 200 kW/m2 | 11.5% | 8.9% | 12.6% | 9.8% | 17.7% | 14.0% |
| SQ req'd at 300 kW/m2 | 17.0% | 13.4% | 18.5% | 14.6% | 25.2% | 20.3% |

**[00114]** Managing heat flux with judicious selection of the fin profile and density, and perhaps changing the routing of the BFW through the economizer, will reduce the amount of required operating subcool and the required steam quality (and the quantity of recycled steam). Maintaining a peak heat flux to less than 50 kW/m$^2$, the required operating subcool can be as low as 3 °C to 5 °C and the required operating steam quality can be as low as 3 % to 5%.

<u>Approach 2: Utilizing a novel flow-path configuration in combination with a pressure-reducing element</u>



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**[00115]** As set out above, in the absence of an auxiliary-vapour stream, incorporating a pressure-reducing element into a conventional flow path is ill suited to satisfying the tolerances associated with steam generation for hydrocarbon recovery. In contrast, the present approach achieves similar results to those set out above with respect to the auxiliary-vapour-stream approach, by combining a novel flow-path configuration with a pressure-reducing element.

**[00116]** Briefly stated, the novel flow-path is configured to attenuate the first-stage heat flux into the feedwater stream as it approaches the pressure-reducing element and, provided the relevant parameters are selected judiciously, this provides sufficient margins at the pressure-reducing element for substantially avoiding the nucleate boiling regime as part of the feedwater water stream is flashed to steam. As the feedwater stream approaches the pressure-reducing element, attenuating the heat flux reduces the subcool required to stay below the onset of nucleate boiling and thus increases the upper temperature limit of the feed-water stream at the inlet to the pressure-reducing element. Higher feedwater-temperatures at the inlet to the pressure-reducing element correlate to higher steam qualities at the outlet of the pressure-reducing element, and the parameters can be configured to ensure that the steam quality at the outlet of the pressure-reducing device is above the threshold required to achieve evaporative heat transfer.

**[00117]** As set out below, attenuating the first-stage heat flux into the feedwater stream as it approaches the pressure-reducing element can be achieved by configuring the flow path of the feedwater stream to run co-current with the flow path of the combustion fluids of the steam generator. In conventional steam generators, the flow path of the feedwater stream runs counter-current to that of the combustion fluids such that the feedwater stream is exposed to progressively higher heat flux as it approaches (and moves through) the nucleate boiling regime. Embodiments of the present disclosure are more strategic in that they manage the operating heat flux and amount of subcool as they approach the pressure-reducing element. In embodiments of the present disclosure, the flow path of the feedwater stream is configured to run co-current with flow path of the combustion gas such that the highest heat flux is applied to the feedwater stream while it is still substantially subcooled. This may serve to decrease the heating capacity of the combustion-gas stream and to increase the temperature of the feedwater stream. The co-current flow relationship thus decreases the temperature differential between the feedwater



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stream and the combustion-gas stream thereby attenuating the heat flux into the feedwater stream as it approaches the pressure-reducing element.

**[00118]** One general aspect includes a method of generating steam for use in a hydrocarbon production process, the method comprising: passing a feedwater stream from a first-stage inlet to a first-stage outlet along a first-stage flow path, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-temperature is maintained below the saturation temperature of the feedwater stream, and (iv) the first-stage flow path is configured to attenuate the first-stage heat flux as the feedwater stream approaches the first-stage outlet. The method further comprises passing the feedwater stream from the first-stage outlet through a pressure-reducing element to a second-stage inlet, wherein the second-stage inlet has a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream. The method further comprises passing the flashed stream from the second-stage inlet to a second-stage outlet along a second-stage flow path, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream. The method further comprises injecting at least a portion of the flashed stream into a hydrocarbon-containing reservoir as injected steam to facilitate the hydrocarbon production process.

**[00119]** One general aspect includes a system for generating steam for a hydrocarbon production process, the system comprising: (i) a radiant section, (ii) an economizer having a lower section that is proximal to the radiant section and an upper section that is proximal to the lower section, and (iii) a combustion-gas flow path that passes from the radiant section to the lower section of the economizer to the upper section of the economizer. The system further comprises a first-stage flow path for passing a feedwater stream through at least a portion of the steam generator from a first-stage inlet to a first-stage outlet, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure by a pressurizing element, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-temperature is maintained below the saturation temperature of the feedwater stream, and (iv) at least part of the first-stage flow path is co-current with the combustion-gas flow path as the feedwater stream



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approaches the first-stage outlet. The system further comprises a pressure-reducing element that connects the first-stage outlet to a second-stage inlet, wherein the pressure-reducing element is configured to reduce the first-stage pressure to a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream. The system further comprises a second-stage flow path for passing the flashed stream through at least a portion of the steam generator from the second-stage inlet to a second-stage outlet, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream. The system further comprises a steam injection section configured to inject at least a portion of the flashed steam stream into a hydrocarbon-containing reservoir as injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

**[00120]** In the context of the present disclosure, the first-stage inlet may take any suitable position along the first-stage flow path. In the context of the present disclosure, the first-stage inlet may comprise a device (such as a valve), or not. For example the first-stage inlet may comprise un-modified pipe. Likewise, the first-stage outlet may take any suitable position along the first-stage flow path and may or may not comprise a device. For example, the first-stage outlet may comprise un-modified pipe, such that the first-stage flow path passes into the pressure-reducing element without restriction. Selecting a suitable positions and configurations for the first-stage inlet and the first-stage outlet is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00121]** In the context of the present disclosure, the first-stage flow path may take any suitable configuration and may pass through various components of a steam generator as exemplified herein.

**[00122]** In the context of the present disclosure, the first stage pressure may vary along the first-stage flow path, or not. In select embodiments of the present disclosure, the first-stage pressure may be set by the pressurizing element and may be between: (i) about 10 MPa and about 15 MPa; (ii) about 15 MPa and about 18 MPa; and/or (iii) about 18 MPa and about 22 MPa. Selecting a suitable first-stage pressure is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.



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**[00123]** In the context of the present disclosure, the first-stage temperature varies along the first-stage flow path as the feedwater stream is heated. In select embodiments of the present disclosure, at the first-stage inlet, the first-stage temperature may be between: (i) about 50 ºC and about 90 ºC; (ii) about 90 ºC and about 150 ºC; and/or (iii) about 150 ºC and about 210 ºC. In select embodiments of the present disclosure, at the first-stage outlet, the first-stage temperature may be between: (i) about 305 ºC and about 335 ºC; (ii) about 335 ºC and about 350 ºC; and/or (iii) about 350 ºC and about 370 ºC. Selecting suitable first-stage temperatures for the first-stage inlet and the first-stage outlet is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00124]** In the context of the present disclosure, the first-stage heat varies along the first-stage flow path as it passes through various components of the steam generator. In select embodiments of the present disclosure, as the first-stage flow path passes through the radiant section, the first-stage average heat flux may be between: (i) about 40 kW/m$^2$ and about 90 kW/m$^2$; and/or (ii) about 50 kW/m$^2$ and about 90 kW/m$^2$, on an inside area basis. In select embodiments of the present disclosure, as the first-stage flow path passes through the shock row of the lower section of the economizer, the first-stage average heat flux in the lower section may be between: (i) about 65 kW/m$^2$ and about 135 kW/m$^2$; and/or (ii) about 75 kW/m$^2$ and about 120 kW/m$^2$, on an inside basis. In select embodiments of the present disclosure, as the first-stage flow path passes through the fifth row of the lower section of the economizer, the first-stage average heat flux in the lower section may be between: (i) about 25 kW/m$^2$ and about 75 kW/m$^2$; and/or (ii) about 35 kW/m$^2$ and about 65 kW/m$^2$, on an inside basis. In select embodiments of the present disclosure, as the first-stage flow path passes through the first finned row in the upper section of the economizer, the first-stage average heat flux in the upper section may be between: (i) about 85 kW/m$^2$ and about 220 kW/m$^2$; and/or (ii) about 110 kW/m$^2$ and about 200 kW/m$^2$, on an inside basis. In select embodiments of the present disclosure, as the first-stage flow path passes through the last finned row in the upper section of the economizer, the first-stage average heat flux in the upper section may be between: (i) about 3 kW/m$^2$ and about 12 kW/m$^2$; and/or (ii) about 2 kW/m$^2$ and about 10 kW/m$^2$, on an inside basis.. Selecting suitable first-stage heat flux values at the various sections of the steam generator is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.



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**[00125]** In the context of the present disclosure, the pressure-reducing element may be a continuous valve (e.g. an automatic modulating valve or a manual valve), a fixed-orifice restriction, or the like. Selecting a pressure-reducing element is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00126]** In the context of the present disclosure, a flashed stream is one which has passed through the pressure-reducing element, such that at least a portion of the steam is in the gas phase as characterized by a non-zero steam quality greater. In select embodiments of the present disclosure, at the second stage inlet, the flashed stream may have a steam quality of between: (i) about 3 % and about 10 %; (ii) about 10 % and about 20 %; and/or (iii) about 20 % and about 30 %. In select embodiments of the present disclosure, at the second stage outlet, the flashed stream may have a steam quality of between: (i) about 60 % and about 75 %; (ii) about 75 % and about 85 %; and/or (iii) about 85 % and about 97 %. Selecting a suitable steam quality at the second-stage inlet and the second-stage outlet is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00127]** In the context of the present disclosure, the second-stage inlet may take any suitable position along the second-stage flow path. In the context of the present disclosure, the second-stage inlet may or may not comprise a device. For example the second-stage inlet may comprise un-modified pipe such that the second-stage flow path passes from the pressure-reducing element without restriction. Likewise, the second-stage outlet may take any suitable position along the second-stage flow path and may or may not comprise a device. For example, the second-stage outlet may comprise un-modified pipe, such that the second-stage flow path passes into a separator without restriction. Selecting a suitable positions and configurations for the second-stage inlet and the second-stage outlet is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00128]** In the context of the present disclosure, the second-stage flow path may take any suitable configuration and may pass through various components of a steam generator as exemplified herein.

**[00129]** In the context of the present disclosure, the second-stage heat flux varies along the second-stage flow path. In select embodiments of the present disclosure, as the first-stage flow path passes through the radiant section, the second-stage average heat



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flux may be between: (i) about 40 $kW/m^2$ and about 80 $kW/m^2$; (ii) about 80 $kW/m^2$ and about 130 $kW/m^2$; and/or (iii) about 130 $kW/m^2$ and about 180 $kW/m^2$, on an inside area basis. Selecting suitable second-stage heat flux values is within the purview of those skilled in the art having benefitted from the teachings of the present disclosure.

**[00130]** **FIG. 14** shows a schematic of a system of generating steam in accordance with an embodiment of the present disclosure. The system comprises a steam generator 1400 that has a radiant section 1402 and an economizer 1404. The economizer 1404 has a lower section 1404a that is proximal to the radiant section 1402 and an upper section 1404b that is proximal to the lower section 1404a. The area connecting the radiant section 1402 and the lower section 1404a of the economizer 1404 may be referred to as the "hog trough".

**[00131]** The steam generator 1400 has a combustion-gas flow path that is generally identified with block arrows in **FIG. 14**. The combustion-gas flow path starts with air/fuel inlets, passes from the radiant section 1402 to the lower section 1404a of the economizer 1404 to the upper section 1404b of the economizer 1404, and exits from an exhaust (not shown). The temperature of the combustion gases generally decreases along the combustion-gas flow path as they dissipate heat as discussed below.

**[00132]** The steam generator 1400 has a first-stage flow path 1406 for passing a feedwater stream 1408 from a first-stage inlet 1410 to a first-stage outlet 1412. The first-stage flow path 1406 passes through the upper section 1404b of the economizer 1404 along a path that is counter-current to the combustion-fuel flow path. In this portion of the first-stage flow path 1406, the feedwater stream 1408 is "preheated" by heat exchange from the combustion gases.

**[00133]** The first-stage flow path 1406 then exits the upper section 1404b of the economizer 1404 and enters the radiant section 1402. This flow path is unconventional – a conventional flow path would enter the upper section 1404a of the economizer 1400. In the present case, as the first-stage flow path 1406 enters the radiant section 1402 where it serpentines several times longitudinally around the periphery thereof. During this portion of the first-stage flow path 1406, the heat flux into the feedwater stream 1408 is relatively high as the temperature differential between the combustion gases and the feedwater stream 1408 is relatively large. However, at this point the feedwater stream 1408 still has significant subcool, such that the relatively high heat flux is not sufficient to induce nucleate boiling.



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Importantly, the first-stage flow path 1406 passing through the radiant section 1402 results leads to substantial heat transfer, and this lessens the temperature differential between the combustion-gas stream and the feedwater stream 1408. For example, the temperature of the combustion-gas stream in the hog trough of the steam generator 1400 may be about 100 ºC lower than that in an analogous steam generator with a conventional flow path.

**[00134]** The first-stage flow path 1406 then enters the lower section 1404a of the economizer 1404 at the bottom and serpentines towards the top of the lower section 1404a. This creates a co-current flow relationship between the first-stage flow path 1406 and the combustion-gas flow path through the lower section 1404a of the economizer 1404. The heat flux into the feedwater stream 1408 is attenuated by the co-current flow relationship. The combustion-gas temperature of the lower section 1404a of the economizer 1400 is substantially lower than that of the radiant section 1402 (and the temperature of the feedwater stream 1408 continues to increase), such that the heat flux into the feedwater stream 1408 during this portion of the first-stage flow path 1406 is further attenuated. This is important as the feedwater stream 1408 continues to approach the onset of nucleate boiling in this portion of the first-stage flow path 1406. As discussed in detail below, attenuating the heat flux into the feedwater stream 1408 allows for a higher feedwater-stream temperature without reaching the onset of nucleate boiling, because the minimum subcool required to prevent nucleate boiling is a function of heat flux.

**[00135]** The first-stage flow path 1406 ends at the first-stage outlet 1412. A pressure-reducing element 1414 links the first-stage outlet 1412 to a second-stage inlet 1416. The pressure-reducing element 1414 is configured to reduce the first-stage pressure to a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream 1408 into a flashed stream 1418 that has a steam quality that exceeds a threshold for mitigating nucleate boiling. In other words, at the second-stage inlet 1416, the flashed stream 1418 has high enough steam content to ensure that evaporative heat transfer is the dominant mechanism, such that the nucleate boiling regime is substantially avoided. For example, a flashed-stream steam quality of about 12 % may be obtained by configuring the pressure-reducing element 1414 to reduce the first-stage pressure from between about 15 MPa and 20 MPa to a second-stage pressure of about 6 MPa to about 10 MPa.

**[00136]** The flashed stream 1418 follows a second-stage flow path 1420 that runs from the second-stage inlet 1416 to a second-stage outlet 1422. At least a portion of the



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second-stage flow path 1420 passes through the radiant section 1402. As the flashed stream 1418 passes through the radiant section 1402, heat flux into the flashed stream 1418 increases the steam quality of the flashed stream 1418. For example the flashed stream 1418 may have a steam quality of about 5 % to about 20 % (or more) at the second stage inlet, and heat flux along the second-stage flow path 1420 may result in the flashed steam 1418 having a steam quality of about 80 % at the second-stage outlet 1422.

**[00137]** The steam generator 1400 may include a number of additional elements. As a first example, the steam generator may include a valve 1424 in the first-stage flow path 1406 that bypasses a portion of the upper section 1404b of the economizer 1404. The valve 1424 may be configured to selectively allow a portion of the feedwater stream 1408 to enter the radiant section 1402 without preheating. As such the valve 1424 may be used to modulate the temperature of the feedwater stream 1408 at the first-stage outlet 1412 to obtain the desired subcool and thus maintain a temperature below the onset of nucleate boiling. Accordingly, the valve 1424 may also be used to modulate the steam quality of the flashed stream at the second-stage inlet 1416.

**[00138]** As a second example, the steam generator 1400 may include a separator 1424 that is configured to separate the flashed stream 1418 into a substantially vapor-phase stream 1426 and a substantially liquid-phase stream 1428. The substantially-vapor-phase stream 1426 may be injected into a hydrocarbon-containing reservoir to facilitate a hydrocarbon production process, and the substantially liquid-phase stream 1428 may be recycled or discarded as blowdown waste.

**[00139]** As a third example, the steam generator 1400 may include a valve 1430 between the stage-two outlet 1422 and the separator 1424. The valve 1430 may be configured to control the dynamic pressure of the flashed steam. Opening the valve 1430 may reduce backpressure such that the dynamic pressure rises. The valve 1430 may be modulated to provide a target dynamic pressure of between about 10,000 $lb/ft/s^2$ and about 20,000 $lb/ft/s^2$, for example.

**[00140]** As noted above, heating a fluid stream above a threshold steam quality may result in dryout conditions (see **FIG. 1**, reference number 118). Like nucleate boiling, dryout conditions may be associated with steam generator fouling such that they represent an upper limit, below which the steam quality of a liquid/vapour stream should be maintained. Accordingly, steam generator parameters may be configured to increase steam quality



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while remaining within lower and upper bounds to avoid nucleate boiling and dryout, respectively.

**[00141]** Dryout conditions may be estimated using, for example, **EQN. 7-10:**

$$x \leq 0.58\exp\left[0.52 - 0.235{We_G}^{0.17} Fr_G^{0.37}\left(\frac{\rho_G}{\rho_L}\right)^{0.25}\left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$ **EQN. 7**

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$ **EQN. 8**

$$Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G) g D_E}$$ **EQN. 9**

$$q_{DNB} = 0.131 \rho_G^{0.5} h_{fg} (g(\rho_L - \rho_G)\sigma)^{0.25}$$ **EQN. 10**

wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in kg/m$^3$);

$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

σ is the surface tension (expressed in N/m).

**[00142]** Dryout conditions may be used as a limit for determining an appropriate flowrate for a feedwater stream and for determining an appropriate (dry) steam generation rate (having regard to the relevant parameters for the steam generator). For example, **FIG.**



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**15A** and **FIG. 15B** show plots of feedwater stream flowrate as a function of steam quality at dryout based on a steam-injection temperature at about 310 ºC for two common coils (NPS 3 Sch 80 coil and NPS4 Sch 80 coil, respectively). In **FIG. 15A** and **FIG. 15B**, plots for a series of heat flux values are identified by reference numbers as set out in Table 7.

**[00143]** Table 7: Reference numbers and heat flux values (on an inside area basis) for the series of plots of **FIG. 15A** and **FIG. 15B.**

| **FIG. 15A** | | **FIG. 15B** | |
|---|---|---|---|
| Reference Number | Heat Flux (kW/m$^2$) | Reference Number | Heat Flux (kW/m$^2$) |
| 1502 | 42 | 1512 | 42 |
| 1504 | 58 | 1514 | 58 |
| 1506 | 74 | 1516 | 74 |
| 1508 | 90 | 1518 | 90 |
| 1510 | 106 | 1520 | 106 |

**[00144]** A typical boiler may operate at, for example, 74 kW/m$^2$ (on an inside area basis). If the desired steam quality is about 80 % at the outlet of the radiant section in the second stage (and/or at the inlet to a separator), the plots 1506 and 1516 indicate maximum feedwater flowrates of about 14,000 kg/hr and about 25,000 kg/hr, respectively (as indicated with dashed lines in each of **FIG. 15A** and **FIG. 15B**. At 82 % steam quality, the maximum feedwater flowrates are about 12,141 kg/hr and about 23,589 kg/hr, and these correlate to maximum dry steam generation rates of about 9,955 kg/hr and about 19,343 kg/hr. Accordingly, suitable parameters for obtaining about a 10,000 BPD dry steam rate may employ four parallel paths of NPS4 Sch80 coil, operating at 20,167 kg/hr flow path and 82% steam quality at the outlet of the second-stage flow path (**FIG. 15B**).

**[00145]** The selected feedwater rate may then be used to determine the minimum steam quality required to surpass the nucleate boiling regime as the flashed stream flows from the second-stage inlet. For example, **FIG. 16A** and **FIG. 16B** show plots of flowrate



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as a function of minimum steam quality for the same steam-injection temperature (about 310 ºC) and for the same coil types (NPS 3 Sch 80 coil and NPS4 Sch 80 coil, respectively). In **FIG. 16A** and **FIG. 16B**, plots for a series of heat flux values are identified by reference numbers as set out in Table 8.

**[00146]** Table 8: Reference numbers and heat flux values (on an inside area basis) for the series of plots of **FIG. 16A** and **FIG. 16B.**

| **FIG. 16A** | | **FIG. 16B** | |
|---|---|---|---|
| Reference Number | Heat Flux (kW/m$^2$) | Reference Number | Heat Flux (kW/m$^2$) |
| 1602 | 42 | 1612 | 42 |
| 1604 | 58 | 1614 | 58 |
| 1606 | 74 | 1616 | 74 |
| 1608 | 90 | 1618 | 90 |
| 1610 | 106 | 1620 | 106 |

**[00147]** Using the same average heat flux (74 kW/m$^2$), and coil selection (NPS4 Sch 80) as above, the selected flow rate (23,589 kg/hr) correlates to minimum steam quality at the stage-two inlet of about 7.5 % (as indicates with dashed lines in **FIG. 16B**).

**[00148]** The selected steam quality at the stage-two inlet may then be used to determine the required subcool at the first-stage outlet. For example, **FIG. 17A** – **FIG. 17D** show plots of steam quality at the second-stage inlet as a function of the first-stage pressure. **FIGS. 17A**, **17B**, **17C**, and **17D**, correspond to injection pressures of 7.4 MPa, 8.6 MPa, 9.9 MPa, and 11.3 MPa, respectively. In **FIG. 17A** – **FIG. 17D** plots for a series of subcool values are identified by reference numbers as set out in Table 9.



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**[00149]** Table 9: Reference numbers and subcool values for the series of plots of **FIG. 17A – FIG. 17D.**

| **FIG. 17A** | | **FIG. 17B** | |
|---|---|---|---|
| Reference Number | Subcool (ºC) | Reference Number | Subcool (ºC) |
| 1702 | 0.01 | 1712 | 0.01 |
| 1704 | 5 | 1714 | 5 |
| 1706 | 10 | 1716 | 10 |
| 1708 | 15 | 1718 | 15 |
| 1710 | 20 | 1720 | 20 |
| **FIG. 17C** | | **FIG. 17D** | |
| Reference Number | Subcool (ºC) | Reference Number | Subcool (ºC) |
| 1722 | 0.01 | 1732 | 0.01 |
| 1724 | 5 | 1734 | 5 |
| 1726 | 10 | 1736 | 10 |
| 1728 | 15 | 1738 | 15 |
| 1730 | 20 | 1740 | 20 |

**[00150]** For a desired second-stage pressure of about 10 MPa, **FIG. 17C** provides the relevant correlation. The minimum steam quality at the second-stage inlet was determined to be about 7.5 %. Targeting a steam quality of 15 % at the second-stage inlet provides a generous margin and, at a typical second-stage pressure of about 18 MPa, the required subcool at the first-stage outlet is about 15 ºC (as identified by the dashed lines in **FIG. 17C**.



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**[00151]** The required subcool is dependent on the first-stage heat flux, the first-stage pressure, the first-stage pipe diameter, and feedwater flow rate. In the present case, the first-stage pipe diameter may be set by the selection of NPS 3 Sch 160 coil, the first stage pressure may be set as discussed with reference to **FIG. 17A – FIG. 17D**, and the feedwater flow rate may be set as discussed with reference to **FIG. 15A – FIG. 15B** . **FIG 18A** and **FIG. 18B**, show plots of minimum subcool as a function of heat flux at first-stage pressures of 15 MPa and 20 MPa, respectively. In **FIG. 18A – FIG. 18B**, plots for a series of feedwater flow rates are identified by reference numbers as set out in Table 10.

**[00152]** Table 10: Reference numbers and feedwater flowrates for the series of plots of **FIG. 18A** and **FIG. 18B.**

| **FIG. 18A** | | **FIG. 18B** | |
|---|---|---|---|
| Reference Number | Flow Rate (kg/h) | Reference Number | Flow Rate (kg/h) |
| 1802 | 10,000 | 1808 | 10,000 |
| 1804 | 20,000 | 1810 | 20,000 |
| 1806 | 30,000 | 1812 | 30,000 |

**[00153]** As discussed above, the heat flux into the feedwater stream as it approaches the first-stage outlet can be attenuated by strategically configuring the first-stage flow path. By configuring the flow path (e.g. co-current flow with the combustion gas in the lower economizer section), and/or the amount of extended surface (e.g. bare tubes at the inlet of the lower economizer section), the operating heat flux at the first-stage outlet can be minimized. For example, the operating heat flux at the first-stage outlet could be managed to less than 60 $kW/m^2$ (on an inside area basis). At 60 $kW/m^2$, 18 MPa, and 20,000 kg/hr, the required subcool to be surpass the nucleate boiling region (and enter the convective heat transfer regime) is only about 3 °C at 20 MPa, and it is only about 4 °C at 15 MPa. In the present case, if the operation is at 15 °C subcool and 18 MPa, the first stage is operating within the convective heat transfer region with 12 °C margin. If 10 °C subcool is achieved, the steam quality at the second-stage inlet will be about 17 %.



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**[00154]** Accordingly, by minimizing the required subcool, the steam quality into the second stage can be maximized for a given first-stage pressure. Alternatively, the first-stage pressure can be minimized for a given operating subcool.

**[00155]** Providing an excess of surface area in the upper section of the economizer (by selecting appropriate fin profiles and densities) provides additional flexibility with respect to the required subcool at the first-stage outlet. This is illustrated in **FIG.19**, which shows plots of heat flux across a set of economizer rows (1 = shock row) for a series of heat release profiles. In **FIG. 19,** the series of heat-release profiles are identified by reference numbers as set out in Table 11.

**[00156]** Table 11: Reference numbers and heat release profiles for the series of plots of **FIG. 19.**

| Reference Number | Heat Release (%) | Reference Number | Flow Rate (kg/h) |
|---|---|---|---|
| 1902 | 100 | 1908 | 70 |
| 1904 | 90 | 1910 | 60 |
| 1906 | 80 | | |

**[00157]** Plotting the operating conditions of the OTSG, the dryout conditions, the required SQ to minimize saturated nucleate boiling, and the required subcool to minimize subcooled nucleate boiling, helps to identify the especially problematic areas for scaling when operating a steam generator with deoiled but otherwise untreated water. **FIG. 20** provides an archetypal plot in this respect for a conventional OTSG design.

**[00158]** In **FIG. 20**, the steam quality along the radiant section is indicated by reference number 2002, and the steam quality threshold for dryout is indicated by reference number 2004. The cross over between the two plots indicates that, for a substantial portion of the flow path, the conventional OTSG operates at a steam quality that exceeds the dryout threshold. This may lead to premature steam generator fouling.

**[00159]** In **FIG. 20**, the steam quality required to surpass the nucleate boiling regime is indicated by reference number 2006. The cross over between the plots 2002 and 2006



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two lines indicates that, for a substantial portion of the flow path, the conventional OTSG operates within the nucleate boiling regime. This may lead to premature steam generator fouling.

**[00160]** In **FIG. 20**, the subcool of the feedwater stream as it passes through the economizer is indicated by reference number 2008, and the required subcool to remain below the onset of nucleate boiling is indicated by reference number 2010. At the inlet to the economizer, the feedwater stream has the highest subcool, and this diminishes as the feedwater stream is heated (right to left on plot 2008). As the feedwater stream approaches the outlet of the economizer, the heat flux increases due to the increase in the combustion-gas temperature. At the same time, the required margin on subcool further diminishes and eventually there is less subcool available than is needed to prevent nucleate boiling (plot 2008 crosses plot 2010). The crossover point indicates that the bulk boiling temperature is reached, and this may lead to premature steam generator fouling. Beyond this point the steam quality starts to increase as the flow path passes through the bottom of the economizer and enters into the radiant section. There is the least amount of steam quality margin in the shock row, and the sudden jump in required SQ is due to the higher heat flux in the shock row.

**[00161]** The foregoing analysis suggests that the expected problematic areas are the bottom of the economizer and the outlet of the radiant section, and this is confirmed with field observations of operating boilers. The flow paths utilized in select embodiments of the present disclosure may reduce these effects as illustrated in **FIG. 21**. **FIG. 21** provides archetypal plots that are analogous to those **FIG. 20**, but configured in accordance with an embodiment of the present disclosure. In the embodiment of **FIG. 21**, the first-stage flow path is routed through the radiant section to minimize the required subcool to prevent nucleate boiling. In the embodiment of **FIG. 21**, the first-stage inlet is at the top of the upper section of the economizer, such that heat exchange with the combustion-gas stream occurs counter-currently. To maximize heat transfer with the combustion-gas stream, the upper section of the economizer has finning on the exterior of the feedwater pipe with different fin heights. The largest fins (i.e. the high-fin sections) are in the upper section of the economizer. Once the feedwater stream leaves the upper section of the economizer, it is directed to the radiant section of the steam generator. Several lengths of pipe in the radiant section preheat the feedwater stream as it flows through the radiant section in a serpentine fashion. The feedwater stream is then directed to the lower section of the economizer,



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where heat exchange occurs co-currently as both the feedwater stream and the combustion gas flow upwards through the economizer. This reduces the required amount of subcool as discussed above.

**[00162]** In the embodiment of **FIG. 21**, the steam quality at the second-stage inlet is increased by flashing through a valve. Flashing through a valve is an adiabatic process, and the enthalpy condition at the second-stage inlet is equal to the enthalpy condition of the outlet of the first stage. Since the desired enthalpy condition of the first-stage outlet is known, the enthalpy condition of at the second-stage inlet is known, and the relative amount of heat absorbed for each stage is known.

**[00163]** As noted above, introducing a pressure-reducing element into a conventional OTSG flow path is likely to produce a steam quality at the inlet to the radiant section that is less than that required to surpass the nucleate boiling regime (such as less than 8% -- see, plots 2002 and 2006 in **FIG. 20**). Since a higher steam quality is desirable at the second-stage inlet, the embodiment of **FIG. 21** captures heat from the radiant section in the first stage as set out above.

**[00164]** In the embodiment of **FIG. 21**bare tubes are used to minimize the heat flux as the feedwater stream approaches the pressure-reducing element (in this case, a valve). This provides a lower required subcool temperature (compared to the conventional design) and allows a higher first-stage outlet temperature for a given operating margin. The higher outlet temperature increases enthalpy – and therefore the steam quality – at the second-stage inlet.

**[00165]** In **FIG. 21**, the steam quality along the radiant section is indicated by reference number 2102. In **FIG. 21**, the steam quality threshold for dryout under peak and average heat flux conditions are indicated by reference numbers 2104a and 2104b, respectively. Plot 2102 does not overlap with plot 2104a, which indicates that the embodiment of **FIG. 21** can be configured to achieve the desired steam quality at the second-stage outlet without exceeding the dryout threshold under average heat flux conditions.

**[00166]** In **FIG. 21**, the steam quality required to surpass the nucleate boiling regime under peak and average heat flux conditions are indicated by reference numbers 2106a and 2106b, respectively. Plot 2102 does not overlap with plot 2106a or 2106b, which



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indicates that the embodiment of **FIG. 21** can be configured to achieve the required steam quality to surpass the nucleate boiling regime after the feedwater stream is flashed.

**[00167]** In **FIG. 21**, the subcool of the feedwater stream as it passes through the economizer is indicated by reference number 2108. In **FIG. 21**, the required subcool to remain below the onset of nucleate boiling under peak and average heat flux conditions are indicated by reference numbers 2110a and 2110b. Plot 2108 does not overlap with plot 2110a or 2110b, which indicates that the embodiment of **FIG. 21** can be configured to remain below the onset of nucleate boiling as the feedwater stream approaches the first-stage outlet. In **FIG. 21**, the starting position plot 2108 is determined by the first-stage pressure. Increasing the first-stage pressure increases the subcool for a given operating temperature. Increasing the first-stage pressure shifts plot 2108 upwards.

Concluding Remarks

**[00168]** It should be understood that, in the context of the present disclosure, while methods and systems are described in terms of “comprising,” “containing,” or “including” various components or steps, the compositions and methods can also “consist essentially of” or “consist of” the various components and steps. Moreover, the indefinite articles “a” or “an”, as used in the description and the claims, are defined herein to mean “one or more than one” of the element that it introduces.

**[00169]** For the sake of brevity, only certain ranges are explicitly disclosed herein. However, ranges from any lower limit may be combined with any upper limit to recite a range not explicitly recited, as well as, ranges from any lower limit may be combined with any other lower limit to recite a range not explicitly recited, in the same way, ranges from any upper limit may be combined with any other upper limit to recite a range not explicitly recited. Additionally, whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range are specifically disclosed. In particular, every range of values (of the form, “from about a to about b,” or, equivalently, “from approximately a to b,” or, equivalently, “from approximately a-b”) disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values even if not explicitly recited. Thus, every point or individual value may serve as its own lower or upper limit combined with any other point or individual value or any other lower or upper limit, to recite a range not explicitly recited.



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**[00170]** Therefore, the present disclosure is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed above are illustrative only, as the present disclosure may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings of the present disclosure. Although individual embodiments are discussed, the disclosure covers all combinations of all those embodiments. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. It is therefore evident that the particular illustrative embodiments disclosed above may be altered or modified and all such variations are considered within the scope of the present disclosure. Moreover, many obvious variations of the embodiments set out herein will suggest themselves to those skilled in the art in light of the present disclosure. Such obvious variations are within the full intended scope of the appended claims.



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**Claims:**

1. A method of generating steam for use in a hydrocarbon production process, the method comprising:

pressurizing a feedwater stream to a first feedwater pressure condition and heating the feedwater stream to a first feedwater temperature condition, to provide a heated feedwater stream;

combining the heated feedwater stream with an auxiliary vapour stream to form a vapour-enhanced stream having a controlled vapour-enhanced steam quality at a second vapour-enhanced temperature condition and a second vapour-enhanced pressure condition;

heating the vapour-enhanced stream in a steam generator to increase the steam quality thereof to provide a heated vapour-enhanced steam stream, wherein the controlled vapour-enhanced steam quality at the second temperature condition and the second pressure condition is maintained so as to mitigate nucleate boiling on a heated steam generator surface within the steam generator during the heating of the vapour-enhanced stream; and

injecting at least a portion of the heated vapour-enhanced steam stream into a hydrocarbon-containing reservoir as an injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

2. The method of claim 1, wherein the auxiliary vapour stream comprises an auxiliary steam.

3. The method of claim 2, wherein the auxiliary steam has a steam quality of greater than about 90%.

4. The method of claim 2 or 3, wherein the auxiliary steam has a temperature of between about 200°C and 350°C, or between about 212°C and about 311°C.

5. The method of any one of claims 2 to 4, wherein the auxiliary steam has an auxiliary steam pressure of between about 2 MPa and about 10 MPa.

6. The method of any one of claims 2 to 5, wherein the auxiliary steam comprises steam generated in a separate boiler from a treated water stream.



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7. The method of any one of claims 1 to 6, wherein the auxiliary vapour stream comprises one or more of a fuel gas, a produced gas, an inert gas, or an oxygen-free gas mixture.

8. The method of any one of claims 1 to 7, wherein the first feedwater pressure condition is between about 12 MPa and about 15 MPa, or at least about 12,500 kPa, or at least about 14,500 kPa.

9. The method of any one of claims 1 to 8, wherein the second vapour-enhanced pressure condition is at least about 3,500 kPa or at least about 5,000 kPa, or at least about 9,500 kPa, or between about 3 MPa and about 12 MPa.

10. The method of any one of claims 1 to 9, wherein the second vapour-enhanced temperature condition is between about 200°C and about 350°C, or between about 234°C and about 325°C.

11. The method of any one of claims 1 to 10, wherein heating the vapour-enhanced steam stream comprises providing a peak heat flux of between about 150 kW/m$^2$ and about 300 kW/m$^2$ and/or providing an average heat flux of between about 50 kW/m$^2$ and about 160 kW/m$^2$, on an inside area basis.

12. The method of any one of claims 1 to 11, wherein heating the feedwater stream to the first feedwater temperature condition comprises heating to a controlled subcooled feedwater temperature so as to mitigate nucleate boiling at the first feedwater pressure condition.

13. The method of claim 12, wherein the controlled subcooled feedwater temperature is at least about 3ºC, 10ºC, 20ºC, 22 ºC, 30ºC or 40ºC subcooled.

14. The method of claim 12 or 13, wherein the controlled subcooled feedwater temperature is subcooled by a subcool, $\Delta\mathrm{T}$, that satisfies the following condition:

$$\Delta\mathrm{T} \geq \frac{q}{0.023 {R_e}^{0.8} {P_r}^{0.4} \frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

wherein:



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$q$ is a local heat flux expressed in W/m$^2$,

$R_e$ is a Reynolds number,

$P_r$ is a Prandtl number,

$k$ is a fluid thermal conductivity expressed in W/m/°C,

$D_e$ is a hydraulic diameter, and

$P$ is a system pressure expressed in Pa.

15. The method of any one of claims 1 to 14, wherein heating the feedwater stream to the first feedwater temperature condition comprises maintaining a peak feedwater heat flux of less than 50 kW/m$^2$, on an inside area basis.

16. The method of any one of claims 1 to 15, wherein heating the feedwater stream to the first feedwater temperature condition comprises providing a first heating mass flux rate of between about 800 kg/m$^2$/s and about 2,500 kg/m$^2$/s.

17. The method of any one of claims 1 to 16, wherein heating the feedwater stream to the first feedwater temperature condition comprises heating the feedwater stream in an economizer section of the steam generator.

18. The method of any one of claims 1 to 17, wherein the controlled vapour-enhanced steam quality is at least about 3%, at least about 5%, at least about 12%, or between about 10% and about 30%.

19. The method of any one of claims 1 to 18, wherein the heated vapour-enhanced steam stream has a heated vapour-enhanced steam quality of at least about 70%, at least about 80%, or at least about 90%.

20. The method of any one of claims 1 to 19, wherein the controlled vapour-enhanced steam quality, $x$, is controlled so as to satisfy the following condition:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}} + 1}$$

wherein:



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$q$ is a local heat flux expressed in W/m$^2$,

$G$ is a mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is a evaporative enthalpy expressed in J/kg,

$\rho_G$ is a vapour density expressed in kg/m$^3$,

$\rho_L$ is a liquid density expressed in kg/m$^3$,

$\mu_L$ is a vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is a liquid phase dynamic viscosity expressed in Pa·s, and,

$B_i$ is a boiling index and is ≤ 0.00015 , or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

21. The method of any one of claims 1 to 20, wherein at least a portion of the heated vapour-enhanced steam stream is recycled to the auxiliary vapour stream as a recycled steam stream.

22. The method of claim 21, wherein between about 3% and about 30% by weight, or between about 5% and about 20% by weight, of the heated vapour-enhanced steam stream is recycled to the auxiliary vapour stream as the recycled steam stream.

23. The method of any one of claims 1 to 22, further comprising separating the heated vapour-enhanced steam stream into a substantially vapour-phase stream and a substantially liquid-phase stream prior to injection of at least a first portion of the substantially vapour-phase stream into the hydrocarbon-containing reservoir.

24. The method of claim 23, wherein a second portion of the substantially vapour-phase stream is recycled to the auxiliary vapour stream as a recycled steam stream.

25. The method of claim 24, wherein the second portion of the substantially vapour-phase stream accounts for between about 3% and about 30% by weight of the substantially vapour-phase stream.

26. The method of any one of claims 23 to 25, wherein the substantially vapour-phase stream accounts for between about 70% and about 95 %, or between about 80% and about 90%, by weight of the heated vapour-enhanced steam stream.



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27. The method of any one of claims 23 to 25, wherein the substantially liquid-phase stream accounts for between about 30% and about 5%, or between about 20% and about 10%, by weight of the heated vapour-enhanced steam stream.

28. The method of any one of claims 21, 22 or 24 to 27, wherein the recycled steam stream is compressed before being combined with the heated feedwater stream.

29. The method of any one of claims 1 to 28, wherein the controlled injected steam quality is at least about 80%, at least about 85%, at least about 90%, at least about 95% or about 100%.

30. The method of any one of claims 1 to 29, wherein the hydrocarbon-containing reservoir is a bitumen-containing reservoir.

31. The method of any one of claims 1 to 30, wherein the hydrocarbon production process comprises steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof.

32. The method of claim 31, wherein the hydrocarbon production process comprises a SAGD process, the controlled injected steam quality is between about 85% and about 100%, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250°C and about 325°C.

33. The method of any one of claims 1 to 32, wherein the steam generator is heat-recovery steam generator (HRSG).

34. The method of claim 33, wherein the HRSG is a natural-circulation steam generator (NCSG), forced-circulation steam generator (FCSG), or once-through steam generator (OTSG).

35. The method of any one of claims 1 to 34, wherein the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L.



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36. The method of any one of claims 1 to 35, wherein the feedwater stream has a hardness content of less than about 25 mg/L, or less than about 15 mg/L.

37. The method of any one of claims 1 to 36, wherein the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L.

38. The method of any one of claims 1 to 37, wherein the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L.

39. The method of any one of claims 1 to 38, wherein the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L.

40. The method of any one of claims 1 to 39, wherein the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU.

41. The method of any one of claims 1 to 40, wherein the heating of the feedwater stream to the first feedwater temperature condition occurs primarily by convective heating and/or substantially in the absence of nucleate boiling.

42. The method of any one of claims 1 to 41, wherein the heating of the vapour-enhanced steam stream occurs primarily by radiative heating and/or substantially in the absence of nucleate boiling.

43. The method of any one of claims 1 to 42, wherein combining the heated feedwater stream with the auxiliary vapour stream is carried out in an eductor having a motive-fluid inlet, a passive-fluid inlet, and a discharge outlet.

44. The method of claim 43, wherein the feedwater stream enters the eductor at the motive fluid inlet, the auxiliary vapour stream enters the eductor at the passive-fluid inlet, and the vapour-enhanced stream exits the eductor at the discharge outlet.

45. The method of any one of claims 1 to 44, wherein the steam quality of the heated vapour-enhanced steam stream is controlled to satisfy the following condition:



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$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We}_G{}^{0.17} Fr_G^{0.37} \left(\frac{\rho_G}{\rho_L}\right)^{0.25} \left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$

$$Fr_G = \frac{G^2}{\rho_G(\rho_{L-}\rho_G)\mathrm{g}D_\mathrm{E}};$$

$$q_{DNB} = 0.131\rho_G^{0.5} h_{fg}(\mathrm{g}(\rho_{L-}\rho_G)\sigma)^{0.25}$$

and wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in $m/s^2$);

$q$ is the local heat flux (expressed in $W/m^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in $W/m^2$);

$G$ is the mass flux (expressed in $kg/m^2/s$);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in $kg/m^3$);

$\rho_L$ is the liquid density (expressed in $kg/m^3$); and

σ is the surface tension (expressed in N/m).

46. A system for generating steam for a hydrocarbon production process, the system comprising:

a pressurizing element that is configured to pressurize a feedwater stream to a first feedwater pressure condition, to provide a pressurized feedwater stream;



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a convective-heating section configured to heat the pressurized feedwater stream to a first feedwater temperature condition, to provide a heated feedwater stream;

a stream connector that is configured combine the heated feedwater stream with an auxiliary vapour stream to form a vapour-enhanced stream having a controlled vapour-enhanced steam quality at a second vapour-enhanced temperature condition and a second vapour-enhanced pressure condition; and,

a radiant-heating section configured to heat the vapour-enhanced stream in a steam generator to increase the steam quality thereof to provide a heated vapour-enhanced steam stream, wherein the controlled vapour-enhanced steam quality at the second temperature condition and the second pressure condition is maintained so as to mitigate nucleate boiling on a heated steam generator surface within the steam generator during the heating of the vapour-enhanced stream; and,

a steam injection section configured to inject at least a portion of the heated vapour-enhanced steam stream into a hydrocarbon-containing reservoir as an injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

47. The system of claim 46, wherein the auxiliary vapour stream comprises an auxiliary steam.

48. The system of claim 47, wherein the auxiliary steam has a steam quality of greater than about 90%.

49. The system of claim 47 or 48, wherein the auxiliary steam has a temperature of between about 200°C and 350°C, or between about 212°C and about 311°C.

50. The system of any one of claims 47 to 49, wherein the auxiliary steam has an auxiliary steam pressure of between about 2 MPa and about 10 MPa.

51. The system of any one of claims 47 to 50, wherein the auxiliary steam comprises steam generated in a separate boiler from a treated water stream.

52. The system of any one of claims 46 to 51, wherein the auxiliary vapour stream comprises one or more of a fuel gas, a produced gas, an inert gas, or an oxygen-free gas mixture.



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53. The system of any one of claims 46 to 52, wherein the first feedwater pressure condition is between about 12 MPa and about 15 MPa, or at least about 12,500 kPa, or at least about 14,500 kPa.

54. The system of any one of claims 46 to 53, wherein the second vapour-enhanced pressure condition is at least about 3,500 kPa or at least about 5,000 kPa, or at least about 9,500 kPa, or between about 3 MPa and about 12 MPa.

55. The system of any one of claims 46 to 54, wherein the second vapour-enhanced temperature condition is between about 200°C and about 350°C, or between about 234°C and about 325°C.

56. The system of any one of claims 46 to 55, wherein heating the vapour-enhanced steam stream comprises providing a peak heat flux of between about 150 kW/m$^2$ and about 300 kW/m$^2$ and/or providing an average heat flux of between about 50 kW/m$^2$ and about 160 kW/m$^2$, on an inside area basis.

57. The system of any one of claims 46 to 56, wherein heating the feedwater stream to the first feedwater temperature condition comprises heating to a controlled subcooled feedwater temperature so as to mitigate nucleate boiling at the first feedwater pressure condition.

58. The system of claim 57, wherein the controlled subcooled feedwater temperature is at least about 3 ºC, 10 ºC, 20 ºC, 22 ºC, 30 ºC or 40 ºC subcooled.

59. The system of claim 57 or 58, wherein the controlled subcooled feedwater temperature is subcooled by a subcool, $\Delta\mathrm{T}$, that satisfies the following condition:

$$\Delta\mathrm{T} \geq \frac{q}{0.023{R_e}^{0.8}{P_r}^{0.4}\frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$R_e$ is a Reynolds number,

$P_r$ is a Prandtl number,

$k$ is a fluid thermal conductivity expressed in W/m/°C,



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$D_e$ is a hydraulic diameter, and

$P$ is a system pressure expressed in Pa.

60. The system of any one of claims 46 to 59, wherein heating the feedwater stream to the first feedwater temperature condition comprises maintaining a peak feedwater heat flux of less than 50 kW/m$^2$ on an inside area basis.

61. The system of any one of claims 46 to 60, wherein heating the feedwater stream to the first feedwater temperature condition comprises providing a first heating mass flux rate of between about 800 kg/m$^2$/s and about 2,500 kg/m$^2$/s.

62. The system of any one of claims 46 to 61, wherein heating the feedwater stream to the first feedwater temperature condition comprises heating the feedwater stream in an economizer section of the steam generator.

63. The system of any one of claims 46 to 62, wherein the controlled vapour-enhanced steam quality is at least about 3%, at least about 5%, at least about 12%, or between about 10% and about 30%.

64. The system of any one of claims 46 to 63, wherein the heated vapour-enhanced steam stream has a heated vapour-enhanced steam quality of at least about 70%, at least about 80%, or at least about 90%.

65. The system of any one of claims 46 to 64, wherein the controlled vapour-enhanced steam quality, $x$, is controlled so as to satisfy the following condition:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}} + 1}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$G$ is a mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is a evaporative enthalpy expressed in J/kg,

$\rho_G$ is a vapour density expressed in kg/m$^3$,



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$\rho_L$ is a liquid density expressed in kg/m$^3$,

$\mu_L$ is a vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is a liquid phase dynamic viscosity expressed in Pa·s, and,

$B_i$ is a boiling index and is ≤ 0.00015, or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

66. The system of any one of claims 46 to 65, wherein at least a portion of the heated vapour-enhanced steam stream is recycled to the auxiliary vapour stream as a recycled steam stream.

67. The system of claim 66, wherein between about 3% and about 30% by weight, or between about 5% and about 20% by weight, of the heated vapour-enhanced steam stream is recycled to the auxiliary vapour stream as the recycled steam stream.

68. The system of any one of claims 46 to 67, further comprising separating the heated vapour-enhanced steam stream into a substantially vapour-phase stream and a substantially liquid-phase stream prior to injection of at least a first portion of the substantially vapour-phase stream into the hydrocarbon-containing reservoir.

69. The system of claim 68, wherein a second portion of the substantially vapour-phase stream is recycled to the auxiliary vapour stream as a recycled steam stream.

70. The system of claim 69, wherein the second portion of the substantially vapour-phase stream accounts for between about 3% and about 30% by weight of the substantially vapour-phase stream.

71. The system of any one of claims 68 to 70, wherein the substantially vapour-phase stream accounts for between about 70% and about 95 %, or between about 80% and about 90%, by weight of the heated vapour-enhanced steam stream.

72. The system of any one of claims 68 to 70, wherein the substantially liquid-phase stream accounts for between about 30% and about 5%, or between about 20% and about 10%, by weight of the heated vapour-enhanced steam stream.



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73. The system of any one of claims 66, 67 or 69 to 72, wherein the recycled steam stream is compressed before being combined with the heated feedwater stream.

74. The system of any one of claims 46 to 73, wherein the controlled injected steam quality is at least about 80%, at least about 85%, at least about 90%, at least about 95% or about 100%.

75. The system of any one of claims 46 to 74, wherein the hydrocarbon-containing reservoir is a bitumen-containing reservoir.

76. The system of any one of claims 46 to 75, wherein the hydrocarbon production process comprises steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof.

77. The system of claim 76, wherein the hydrocarbon production process comprises a SAGD process, the controlled injected steam quality is between about 85% and about 100%, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250°C and about 325°C.

78. The system of any one of claims 46 to 77, wherein the steam generator is heat-recovery steam generator (HRSG).

79. The system of claim 78, wherein the HRSG is a natural-circulation steam generator (NCSG), forced-circulation steam generator (FCSG), or once-through steam generator (OTSG).

80. The system of any one of claims 46 to 79, wherein the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L.

81. The system of any one of claims 46 to 80, wherein the feedwater stream has a hardness content of less than about 25 mg/L, or less than about 15 mg/L.



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82. The system of any one of claims 46 to 81, wherein the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L.

83. The system of any one of claims 46 to 82, wherein the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L.

84. The system of any one of claims 46 to 83, wherein the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L.

85. The system of any one of claims 46 to 84, wherein the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU.

86. The system of any one of claims 46 to 85, wherein the heating of the feedwater stream to the first feedwater temperature condition occurs primarily by convective heating and/or substantially in the absence of nucleate boiling.

87. The system of any one of claims 46 to 86, wherein the heating of the vapour-enhanced steam stream occurs primarily by radiative heating and/or substantially in the absence of nucleate boiling.

88. The system of any one of claims 46 to 87, wherein combining the heated feedwater stream with the auxiliary vapour stream is carried out in an eductor having a motive-fluid inlet, a passive-fluid inlet, and a discharge outlet.

89. The system of claim 88, wherein the feedwater stream enters the eductor at the motive fluid inlet, the auxiliary vapour stream enters the eductor at the passive-fluid inlet, and the vapour-enhanced stream exits the eductor at the discharge outlet.

90. The system of any one of claims 46 to 88, wherein the steam quality of the heated vapour-enhanced steam stream is controlled to satisfy the following condition:

$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We}_G{}^{0.17} Fr_G^{0.37}\left(\frac{\rho_G}{\rho_L}\right)^{0.25}\left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:



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$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$

$$Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G) g D_E};$$

$$q_{DNB} = 0.131 \rho_G^{0.5} h_{fg} (g(\rho_L - \rho_G)\sigma)^{0.25}$$

and wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in kg/m$^3$);

$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

$\sigma$ is the surface tension (expressed in N/m).

91. A method of generating steam for use in a hydrocarbon production process, the method comprising:

passing a feedwater stream from a first-stage inlet to a first-stage outlet along a first-stage flow path, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-stage temperature is maintained below the saturation temperature of the feedwater stream, and (iv) the first-stage flow path is configured to attenuate the first-stage heat flux as the feedwater stream approaches the first-stage outlet;



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passing the feedwater stream from the first-stage outlet through a pressure-reducing element to a second-stage inlet, wherein the second-stage inlet has a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream;

passing the flashed stream from the second-stage inlet to a second-stage outlet along a second-stage flow path, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream; and

injecting at least a portion of the flashed stream into a hydrocarbon-containing reservoir as injected steam to facilitate the hydrocarbon production process.

92. The method of claim 91, wherein the first-stage flow path is co-current with a combustion-gas flow path as the feedwater stream approaches the first-stage outlet.

93. The method of claim 91 or 92, wherein as the feedwater stream approaches the first-stage outlet, the first-stage flow path comprises bare tube.

94. The method of any one of claims 91 to 93, wherein the feedwater stream approaches the first-stage outlet in a lower section of an economizer.

95. The method of claim 94, wherein the first-stage average heat flux is between about 75 $kW/m^2$ and about 120 $kW/m^2$, on an inside surface area basis, as the feedwater stream approaches a shock row in the lower section of the economizer.

96. The method of any one of claims 91 to 95, wherein the feedwater stream approaches the first-stage outlet after passing through a radiant section.

97. The method of claim 96, wherein the first-stage average heat flux is between about 50 $kW/m^2$ and about 90 $kW/m^2$, on an inside area basis, as the feedwater stream passes through the radiant section.



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98. The method of claim 96 or 97, wherein the feedwater stream passes through an upper section of an economizer before passing through the radiant section.

99. The method of claim 98, the first-stage average heat flux is between about 110 kW/m$^2$ and about 200 kW/m$^2$, on an inside area basis, as the feedwater stream passes a first finned row in the upper section of the economizer.

100. The method of any one of claims 91 to 99, wherein the steam quality of the flashed stream is controlled to satisfy the following condition:

$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We_G}^{0.17} Fr_G^{0.37} \left(\frac{\rho_G}{\rho_L}\right)^{0.25} \left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};$$

$$Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G) \mathrm{g} D_\mathrm{E}};$$

$$q_{DNB} = 0.131\rho_G^{0.5} h_{fg} (\mathrm{g}(\rho_L - \rho_G)\sigma)^{0.25}$$

and wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);

$Fr_G$ is the Froude Number (dimensionless);

g is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);



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$\rho_G$ is the vapour density (expressed in kg/m$^3$);

$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

$\sigma$ is the surface tension (expressed in N/m).

101. The method of any one of claims 91 to 100, wherein the first-stage pressure is between about 15 MPa and about 22 MPa.

102. The method of any one of claims 91 to 101, wherein second-stage pressure is between about 6 MPa and about 11 MPa.

103. The method of any one of claims 91 to 102, wherein the first-stage temperature is between about 340 ºC and about 360 ºC at the first-stage outlet.

104. The method of any one of claims 91 to 102, wherein the first-stage temperature is at least about 3 ºC, 10 ºC, 15 ºC, or 20 ºC subcooled as the feedwater stream approaches the first-stage outlet.

105. The method of any one of claims 91 to 104, wherein as the feedwater stream approaches the first-stage outlet the first-stage temperature is subcooled by a subcool, $\Delta\mathrm{T}$, that satisfies the following condition:

$$\Delta\mathrm{T} \geq \frac{q}{0.023{R_e}^{0.8}{P_r}^{0.4}\frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$R_e$ is a Reynolds number,

$P_r$ is a Prandtl number,

$k$ is a fluid thermal conductivity expressed in W/m/°C,

$D_e$ is a hydraulic diameter, and

$P$ is a system pressure expressed in Pa.



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106. The method of any one of claims 91 to 105, wherein the steam quality of the flashed stream at the second-stage inlet is at least about 3 %, at least about 5 %, at least about 12 %, or between about 10 % and about 30 %.

107. The method of any one of claims 91 to 106, wherein the flashed stream has a steam quality of at least about 70%, at least about 80%, or at least about 90% at the second-stage outlet.

108. The method of any one of claims 91 to 107, wherein the steam quality, $x$, of the flashed stream is controlled so as to satisfy the following condition at the second-stage inlet:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}}+1}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$G$ is a mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is a evaporative enthalpy expressed in J/kg,

$\rho_G$ is a vapour density expressed in kg/m$^3$,

$\rho_L$ is a liquid density expressed in kg/m$^3$,

$\mu_L$ is a vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is a liquid phase dynamic viscosity expressed in Pa·s, and

$B_i$ is a boiling index and is ≤ 0.00015, or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

109. The method of any one of claims 91 to 108, wherein the steam quality of the portion of the flashed stream that is injected into the hydrocarbon-containing reservoir is at least about 80%, at least about 85%, at least about 90%, at least about 95%, or about 100%.

110. The method of any one of claims 91 to 109, wherein the hydrocarbon-containing reservoir is a bitumen-containing reservoir.



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111. The method of any one of claims 91 to 110, wherein the hydrocarbon production process comprises steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof.

112. The method of claim 111, wherein the hydrocarbon production process comprises a SAGD process, the controlled injected steam quality is between about 85% and about 100%, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250 °C and about 325 °C.

113. The method of any one of claims 91 to 112, wherein the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L.

114. The method of any one of claims91 to 113, wherein the feedwater stream has a hardness content of less than about 25 mg/L, or less than about 15 mg/L.

115. The method of any one of claims 91 to 114, wherein the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L.

116. The method of any one of claims 91 to 115, wherein the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L.

117. The method of any one of claims 91 to 116, wherein the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L.

118. The method of any one of claims 91 to 117, wherein the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU.

119. A system for generating steam for a hydrocarbon production process, the system comprising:

a steam generator comprising: (i) a radiant section, (ii) an economizer having a lower section that is proximal to the radiant section and an upper section that is proximal to the lower



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section, and (iii) a combustion-gas flow path that passes from the radiant section to the lower section of the economizer to the upper section of the economizer;

a first-stage flow path for passing a feedwater stream through at least a portion of the steam generator from a first-stage inlet to a first-stage outlet, wherein along the first-stage flow path: (i) the feedwater stream is pressurized to a first-stage pressure by a pressurizing element, (ii) the feedwater stream is heated to a first-stage temperature by a first-stage heat flux, (iii) the first-temperature is maintained below the saturation temperature of the feedwater stream, and (iv) at least part of the first-stage flow path is co-current with the combustion-gas flow path as the feedwater stream approaches the first-stage outlet;

a pressure-reducing element that connects the first-stage outlet to a second-stage inlet, wherein the pressure-reducing element is configured to reduce the first-stage pressure to a second-stage pressure that is sufficiently lower than the first-stage pressure to convert the feedwater stream into a flashed stream;

a second-stage flow path for passing the flashed stream through at least a portion of the steam generator from the second-stage inlet to a second-stage outlet, wherein: (i) at the second-stage inlet the flashed stream has a steam quality that exceeds a threshold for mitigating nucleate boiling along a heated surface of the second-stage flow path, and (ii) the flashed stream is heated along the second-stage flow path by a second-stage heat flux to increase the steam quality of the flashed stream; and

a steam injection section configured to inject at least a portion of the flashed steam stream into a hydrocarbon-containing reservoir as injected steam at a controlled injected steam quality to facilitate the hydrocarbon production process.

120. The system of claim 119, wherein as the feedwater stream approaches the first-stage outlet, the first-stage flow path comprises bare tube.

121. The system of claim 119 or 120, wherein the feedwater stream approaches the first-stage outlet in the lower section of the economizer.



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122. The system of claim 121, wherein the first-stage average heat flux is between about 75 kW/m$^2$ and about 120 kW/m$^2$, on an inside area basis, as the feedwater stream approaches a shock row in the lower section of the economizer.

123. The system of any one of claims 119 to 122, wherein the feedwater stream approaches the first-stage outlet after passing through the radiant section.

124. The system of claim 123, wherein the first-stage heat flux is between about 50 kW/m$^2$ and about 90 kW/m$^2$, on an inside area basis, as the feedwater stream passes through the radiant section.

125. The system of claim 123 or 124, wherein the feedwater stream passes through the upper section of the economizer before passing through the radiant section.

126. The system of claim 125, wherein the first-stage heat flux is between about 110 kW/m$^2$ and about 200 kW/m$^2$, on an inside area basis, as the feedwater stream passes through a first finned row in the upper section of the economizer.

127. The system of any one of claims 119 to 126, wherein the steam quality of the flashed stream is controlled to satisfy the following condition:

$$x \leq 0.58\exp\left[0.52 - 0.235\mathrm{We_G}^{0.17} Fr_G^{0.37} \left(\frac{\rho_G}{\rho_L}\right)^{0.25} \left(\frac{q}{q_{DNB}}\right)^{0.70}\right]$$

wherein:

$$We_G = \frac{G^2 D_E}{\rho_G \sigma};\ Fr_G = \frac{G^2}{\rho_G(\rho_L - \rho_G)\mathrm{g}D_\mathrm{E}}$$

$$q_{DNB} = 0.131\rho_G^{0.5} h_{fg}(\mathrm{g}(\rho_L - \rho_G)\sigma)^{0.25}$$

and wherein:

$x$ is the steam quality transition to dryout conditions (expressed in mass fraction);

$D_e$ is the hydraulic diameter (expressed in m);



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$Fr_G$ is the Froude Number (dimensionless);

$g$ is the acceleration due to gravity (expressed in m/s$^2$);

$q$ is the local heat flux (expressed in W/m$^2$);

$q_{DNB}$ is the heat flux at departure from nucleate boiling (expressed in W/m$^2$);

$G$ is the mass flux (expressed in kg/m$^2$/s);

$h_{fg}$ is the evaporative enthalpy (expressed in J/kg);

$We_G$ is Weber Number (dimensionless);

$\rho_G$ is the vapour density (expressed in kg/m$^3$);

$\rho_L$ is the liquid density (expressed in kg/m$^3$); and

$\sigma$ is the surface tension (expressed in N/m).

128. The system of any one of claims 119 to 127, wherein the first-stage pressure is between about 15 MPa and about 22 MPa.

129. The system of any one of claims 119 to 128, wherein second-stage pressure is between about 6 MPa and about 11 MPa.

130. The system of any one of claims 119 to 129, wherein the first-stage temperature is between about 340 ºC and about 360 ºC at the first-stage outlet.

131. The system of any one of claims 119 to 130, wherein the first-stage temperature is at least about 3 ºC, 10 ºC, 15 ºC, or 20 ºC subcooled as the feedwater stream approaches the first-stage outlet.

132. The system of any one of claims 119 to 130, wherein as the feedwater stream approaches the first-stage outlet the first-stage temperature is subcooled by a subcool, $\Delta\mathrm{T}$, that satisfies the following condition:

$$\Delta\mathrm{T} \geq \frac{q}{0.023{R_e}^{0.8}{P_r}^{0.4}\frac{k}{D_e}} - \frac{5}{9}\left(\frac{q}{0.00176 * P^{1.156}}\right)^{\frac{P^{0.0239}}{2.83}}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$R_e$ is a Reynolds number,



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$P_r$ is a Prandtl number,

$k$ is a fluid thermal conductivity expressed in W/m/°C,

$D_e$ is a hydraulic diameter, and

$P$ is a system pressure expressed in Pa.

133. The system of any one of claims 119 to 132, wherein the steam quality of the flashed stream at the second-stage inlet is at least about 3 %, at least about 5 %, at least about 12 %, or between about 10 % and about 20 %.

134. The system of any one of claims 119 to 133, wherein the flashed stream has a steam quality of at least about 70%, at least about 80%, or at least about 90% at the second-stage outlet.

135. The system of any one of claims 119 to 134, wherein the steam quality, $x$, of the flashed stream is controlled so as to satisfy the following condition at the second-stage inlet:

$$x \geq \frac{1}{\left(\frac{Bi}{\frac{q}{Gh_{fg}}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}}\right)^{\frac{1}{0.9}} + 1}$$

wherein:

$q$ is a local heat flux expressed in W/m$^2$,

$G$ is a mass flux expressed in kg/m$^2$/s,

$h_{fg}$ is a evaporative enthalpy expressed in J/kg,

$\rho_G$ is a vapour density expressed in kg/m$^3$,

$\rho_L$ is a liquid density expressed in kg/m$^3$,

$\mu_L$ is a vapour phase dynamic viscosity expressed in Pa·s,

$\mu_G$ is a liquid phase dynamic viscosity expressed in Pa·s, and

$B_i$ is a boiling index and is ≤ 0.00015, or ≤ 0.00020, or in the range of 0.00010 to 0.00025.

136. The system of any one of claims 117 to 135, wherein the steam quality of the portion of the flashed stream that is injected into the hydrocarbon-containing reservoir is at least about 80%, at least about 85%, at least about 90%, at least about 95%, or about 100%.



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137. The system of any one of claims 119 to 127, wherein the hydrocarbon-containing reservoir is a bitumen-containing reservoir.

138. The system of any one of claims 119 to 137, wherein the hydrocarbon production process comprises steam assisted gravity drainage, cyclic steam stimulation, a solvent driven process, a solvent dominant process, or a combination thereof.

139. The system of claim 138, wherein the hydrocarbon production process comprises a SAGD process, the controlled injected steam quality is between about 85% and about 100%, the injected steam is at an injection pressure of between about 4 MPa and about 11 MPa, and the injected steam is at an injection temperature of between about 250 °C and about 325 °C.

140. The system of any one of claims 119 to 139, wherein the feedwater stream has a silica content of less than about 250 mg/L, or less than about 50 mg/L.

141. The system of any one of claims 119 to 140, wherein the feedwater stream has a hardness content of less than about 25 mg/L, or less than about 15 mg/L.

142. The system of any one of claims 119 to 141, wherein the feedwater stream has a total suspended solids content of less than about 200 mg/L, or less than about 5 mg/L.

143. The system of any one of claims 119 to 142, wherein the feedwater stream has a soluble organics content of less than about 500 mg/L, or less than about 400 mg/L.

144. The system of any one of claims 119 to 142, wherein the feedwater stream has a residual oil content of less than about 200 mg/L, or less than about 2.0 mg/L.

145. The system of any one of claims 119 to 143, wherein the feedwater stream has a turbidity of less than about 250 NTU ppm, or less than about 5 NTU.



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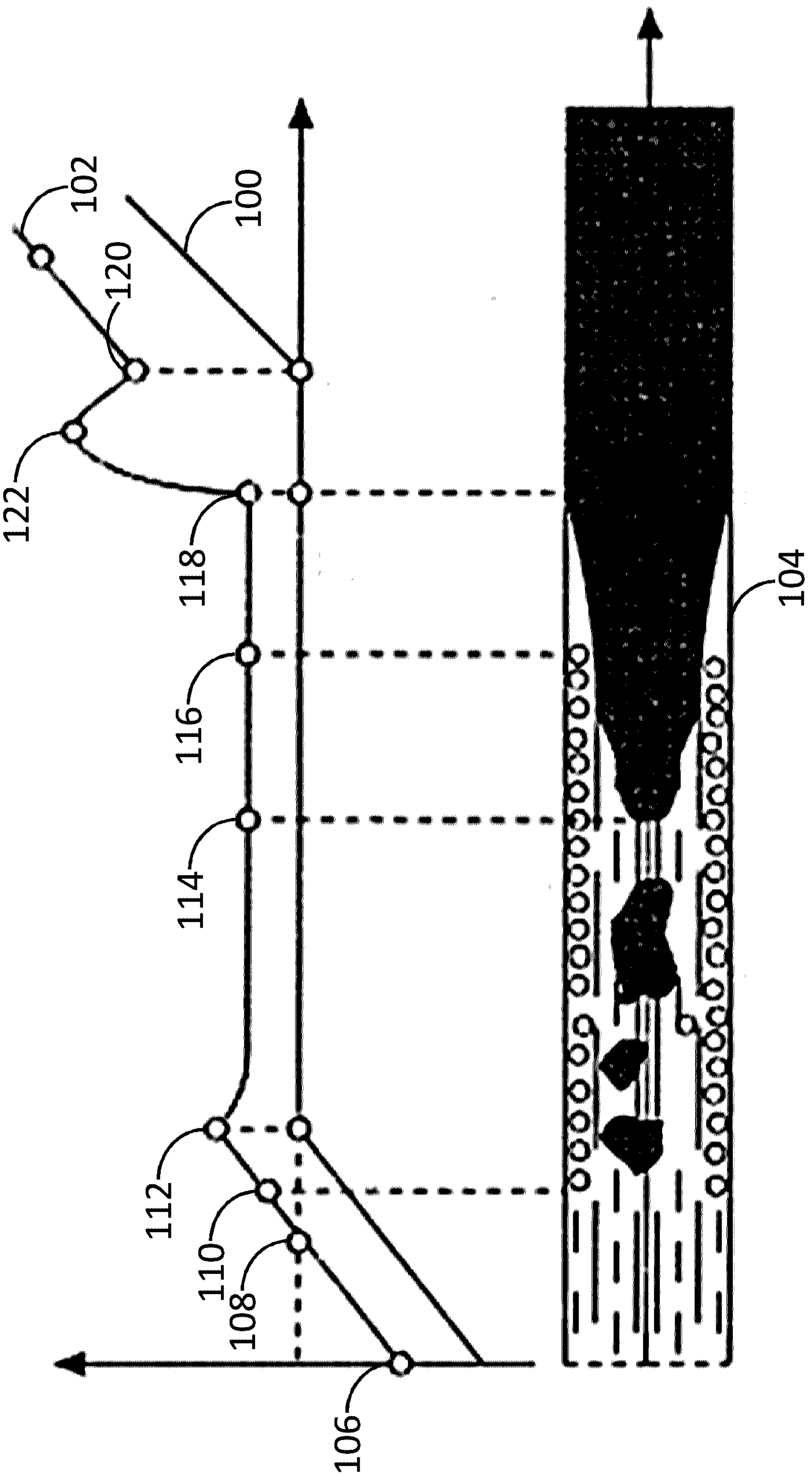



FIG. 1

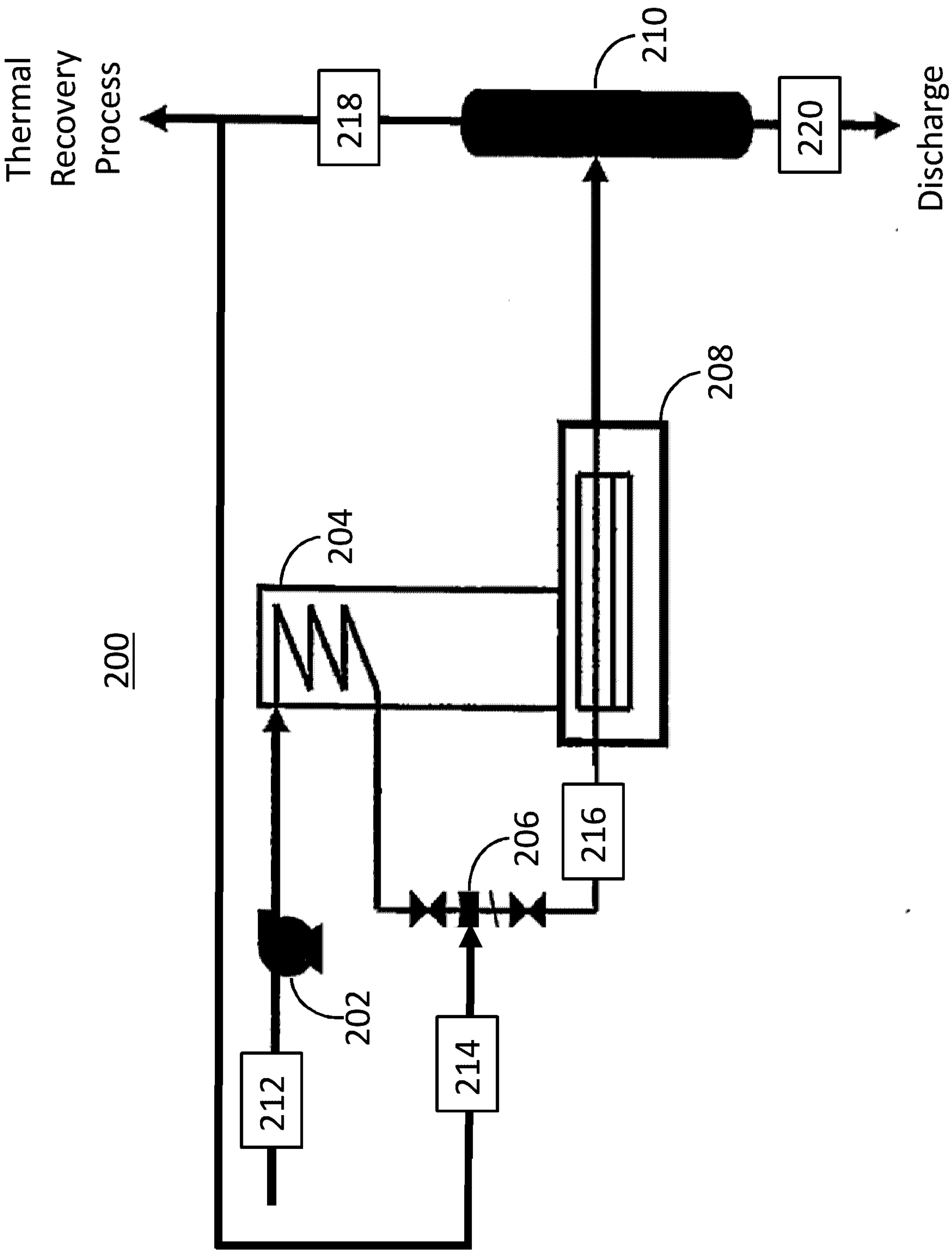

Thermal Recovery Process
218
210
220
Discharge
208
204
200
216
206
202
212
214

FIG. 2

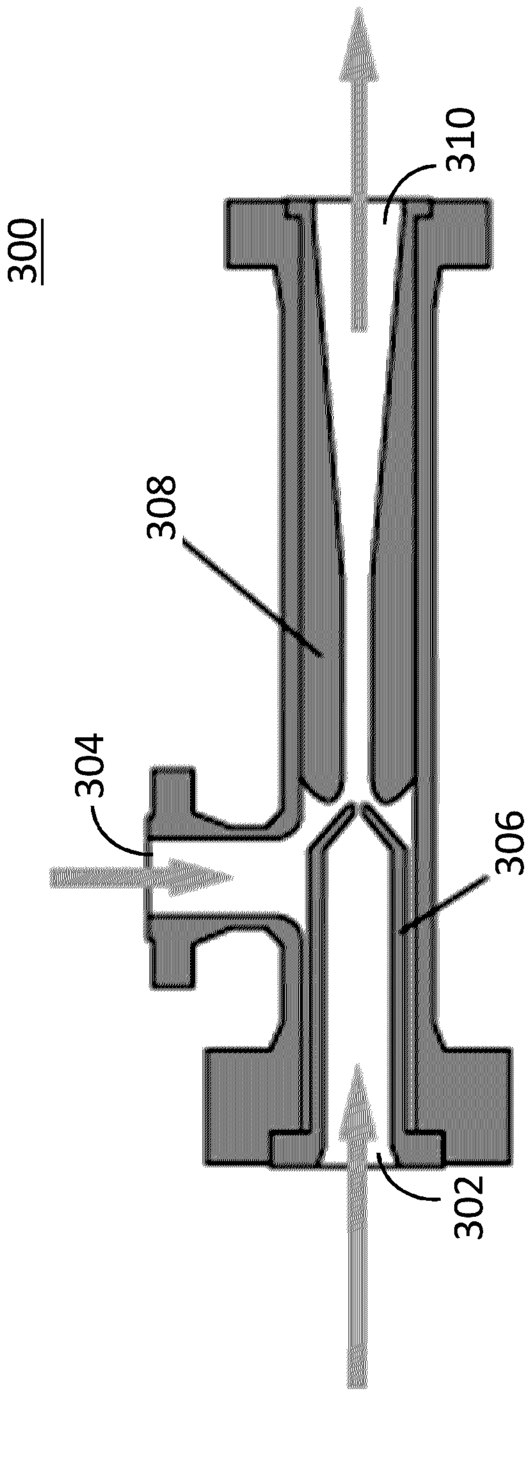



FIG. 3A

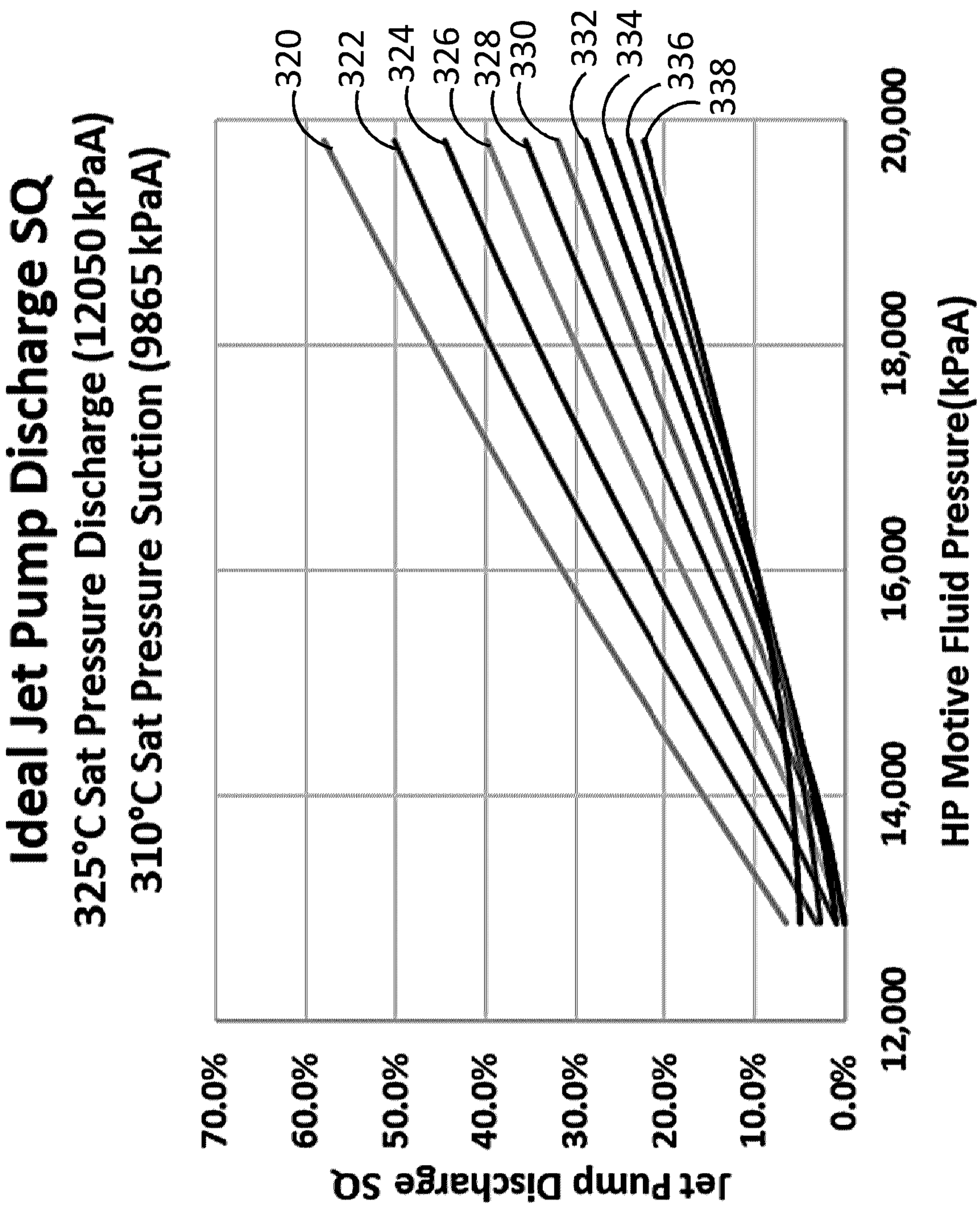

Ideal Jet Pump Discharge SQ
325°C Sat Pressure Discharge (12050 kPaA)
310°C Sat Pressure Suction (9865 kPaA)
Jet Pump Discharge SQ
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
12,000
14,000
16,000
18,000
20,000
HP Motive Fluid Pressure(kPaA)
320
322
324
326
328
330
332
334
336
338

FIG. 3B

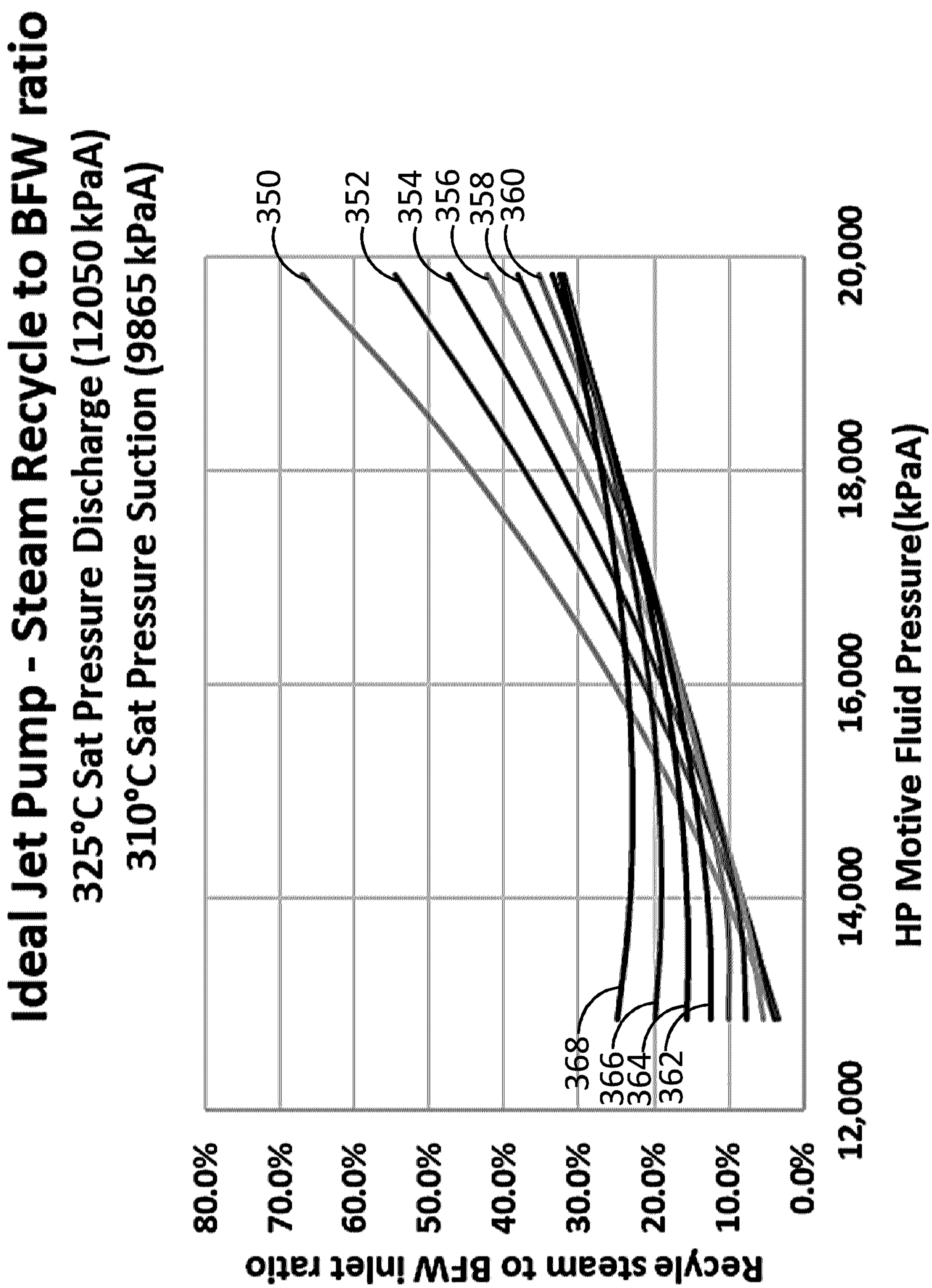

Ideal Jet Pump - Steam Recycle to BFW ratio
325°C Sat Pressure Discharge (12050 kPaA)
310°C Sat Pressure Suction (9865 kPaA)
Recyle steam to BFW inlet ratio
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
12,000
14,000
16,000
18,000
20,000
HP Motive Fluid Pressure(kPaA)
350
352
354
356
358
360
368
366
364
362

FIG. 3C

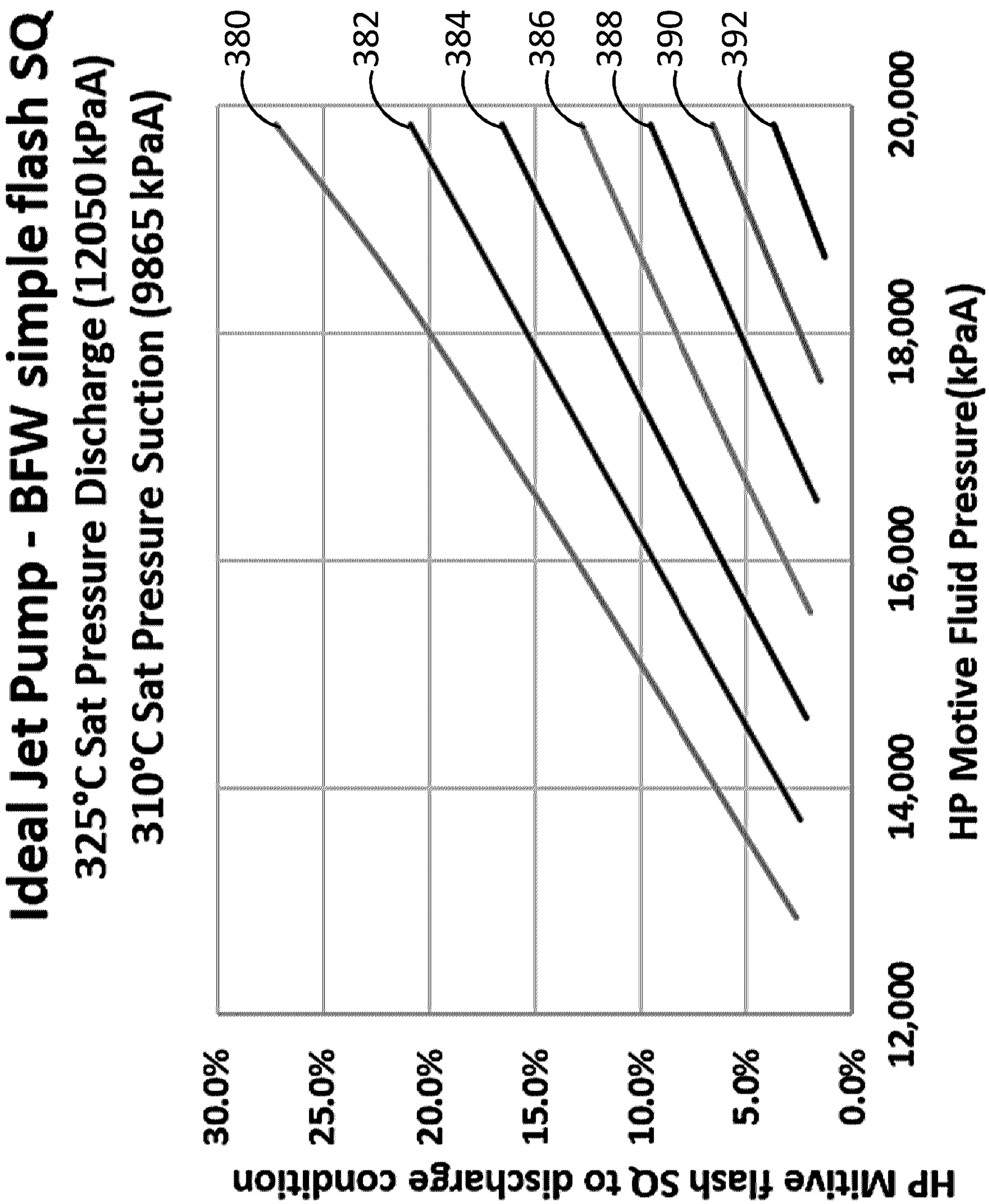

Ideal Jet Pump - BFW simple flash SQ
325°C Sat Pressure Discharge (12050 kPaA)
310°C Sat Pressure Suction (9865 kPaA)
HP Mitive flash SQ to discharge condition
HP Motive Fluid Pressure(kPaA)
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
12,000
14,000
16,000
18,000
20,000
380
382
384
386
388
390
392

FIG. 3D

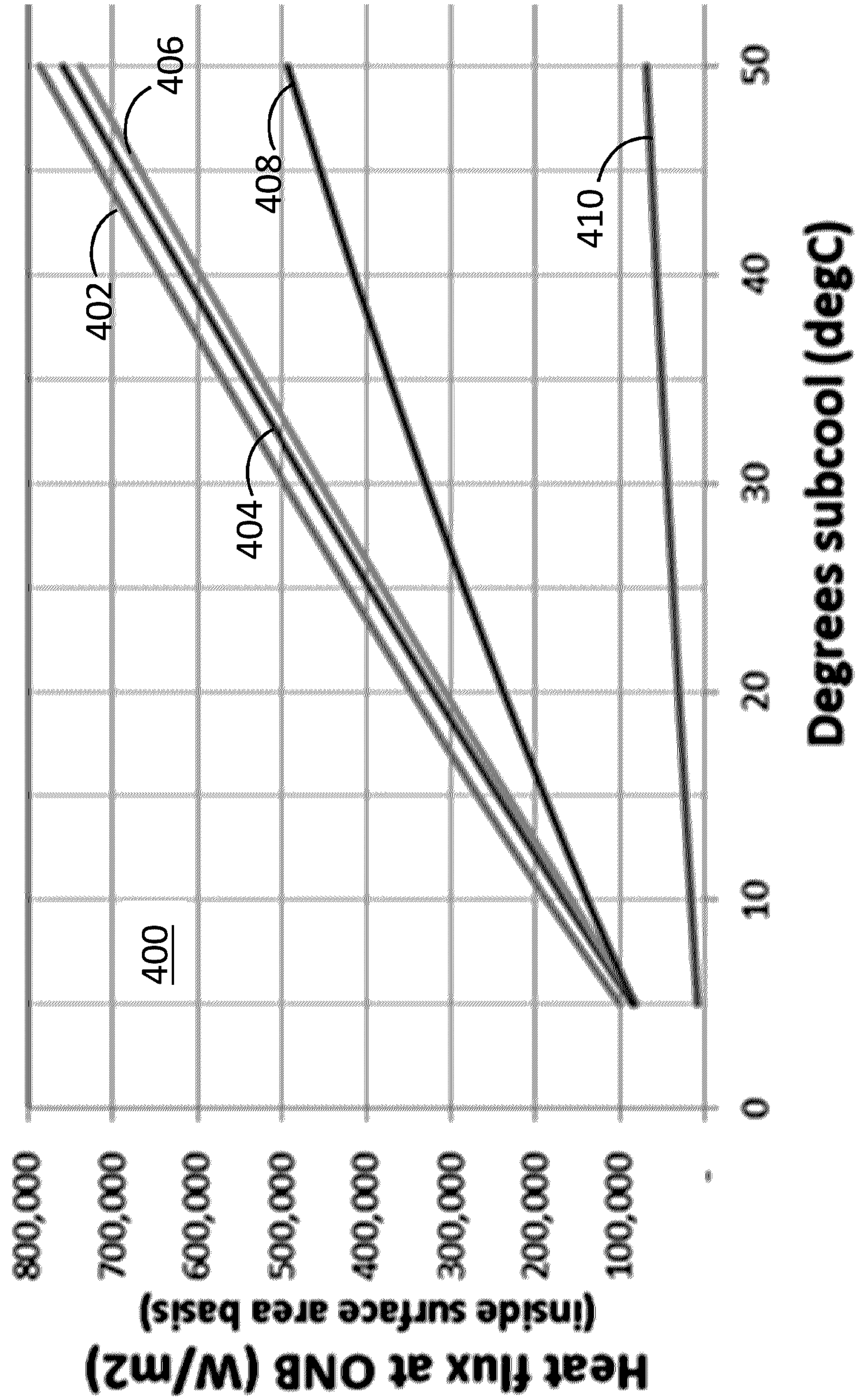



FIG. 4

Date Reçue/Date Received 2020-05-13

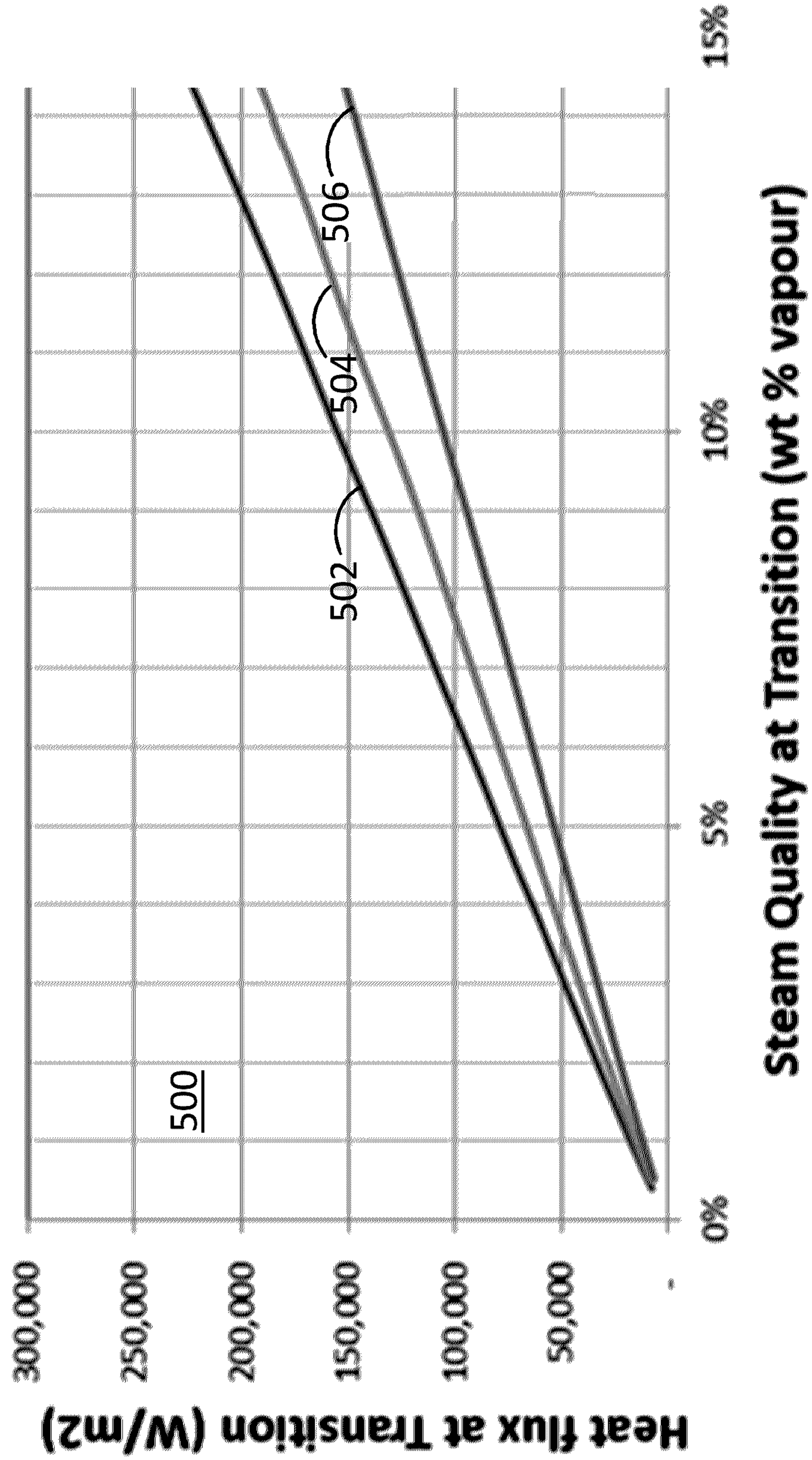
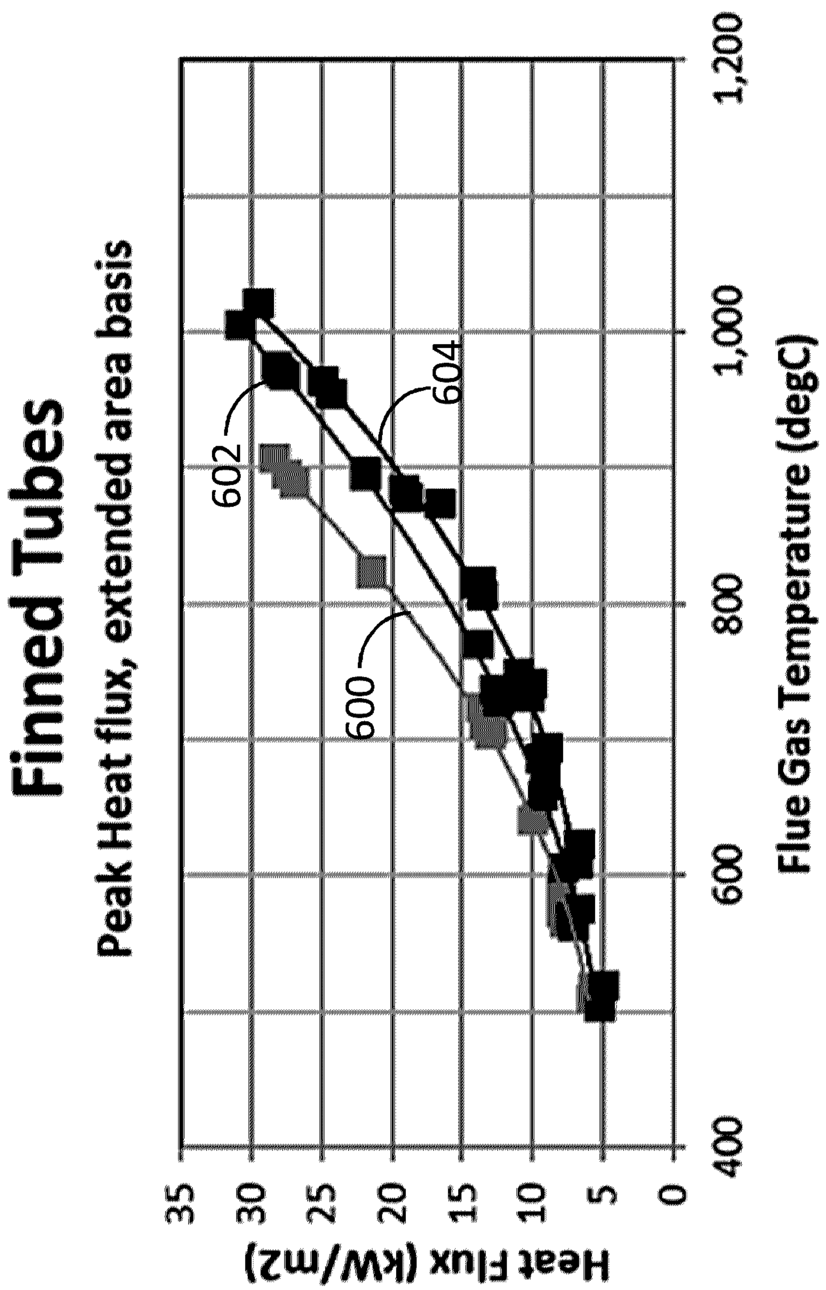
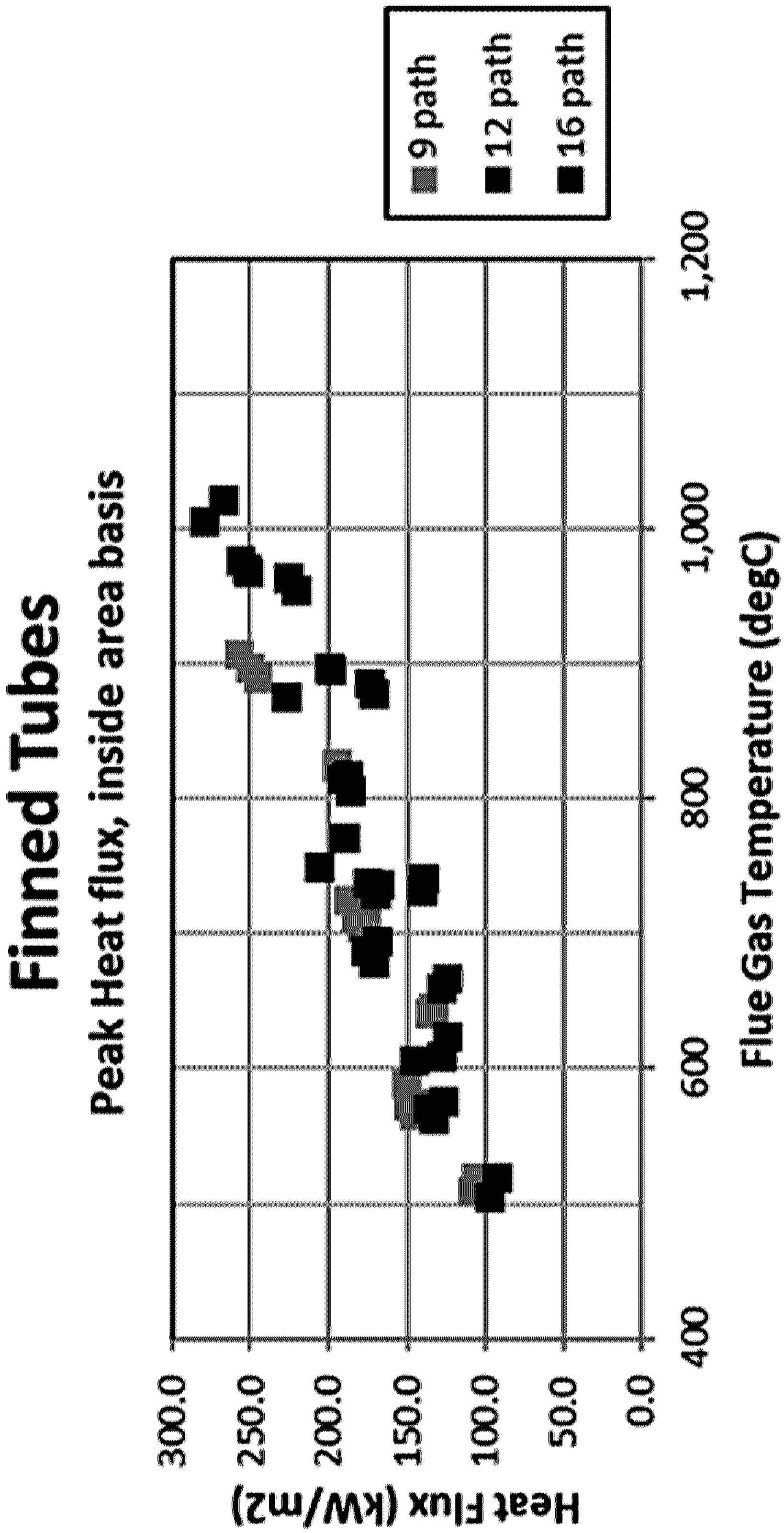

500
Heat flux at Transition (W/m2)
300,000
250,000
200,000
150,000
100,000
50,000
-
0%
5%
10%
15%
Steam Quality at Transition (wt % vapour)
502
504
506

FIG. 5



Finned Tubes
Peak Heat flux, extended area basis
Heat Flux (kW/m2)
35
30
25
20
15
10
5
0
400
600
800
1,000
1,200
Flue Gas Temperature (degC)
600
602
604


FIG. 6



Finned Tubes
Peak Heat flux, inside area basis
Heat Flux (kW/m2)
300.0
250.0
200.0
150.0
100.0
50.0
0.0
400
600
800
1,000
1,200
Flue Gas Temperature (degC)
9 path
12 path
16 path


FIG. 7

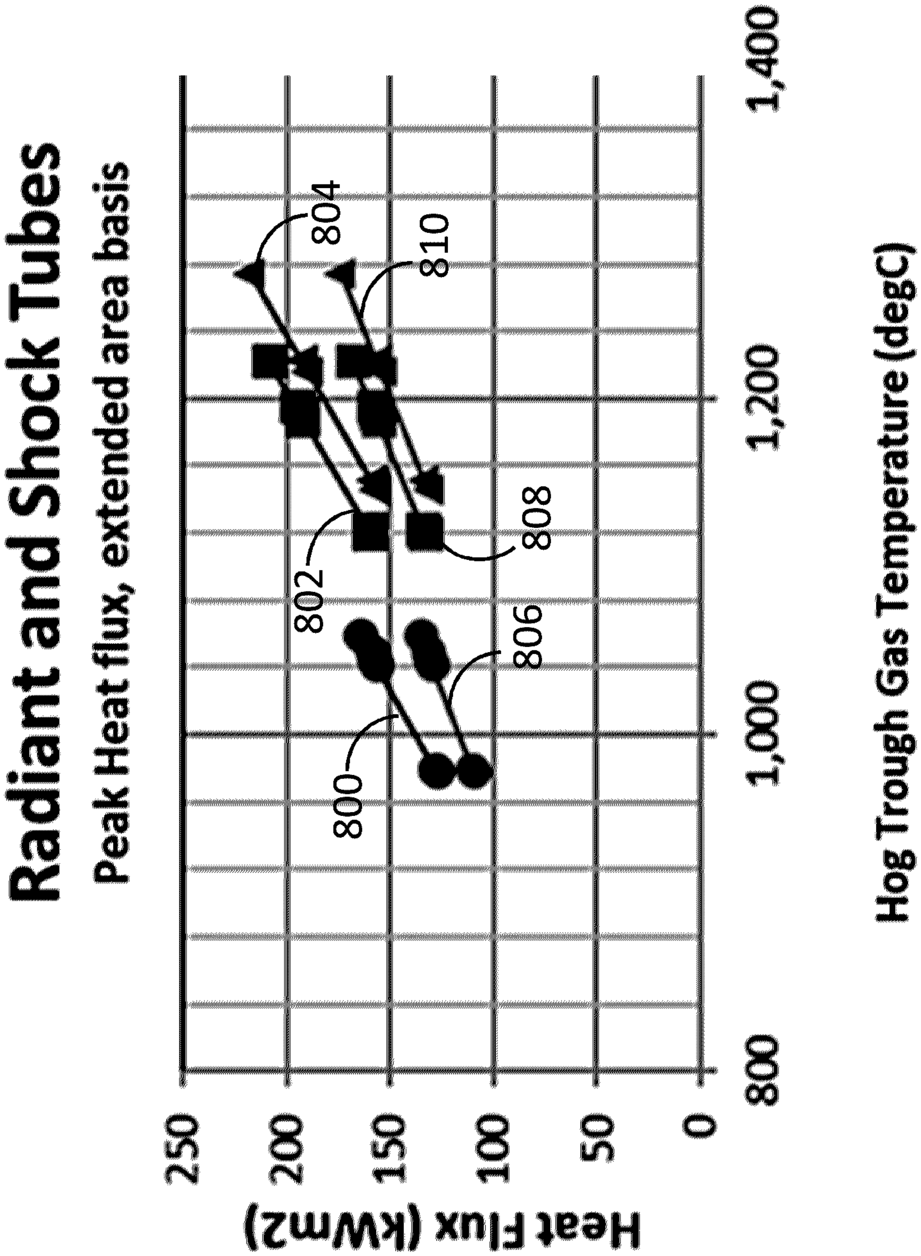



FIG. 8

Date Reçue/Date Received 2020-05-13

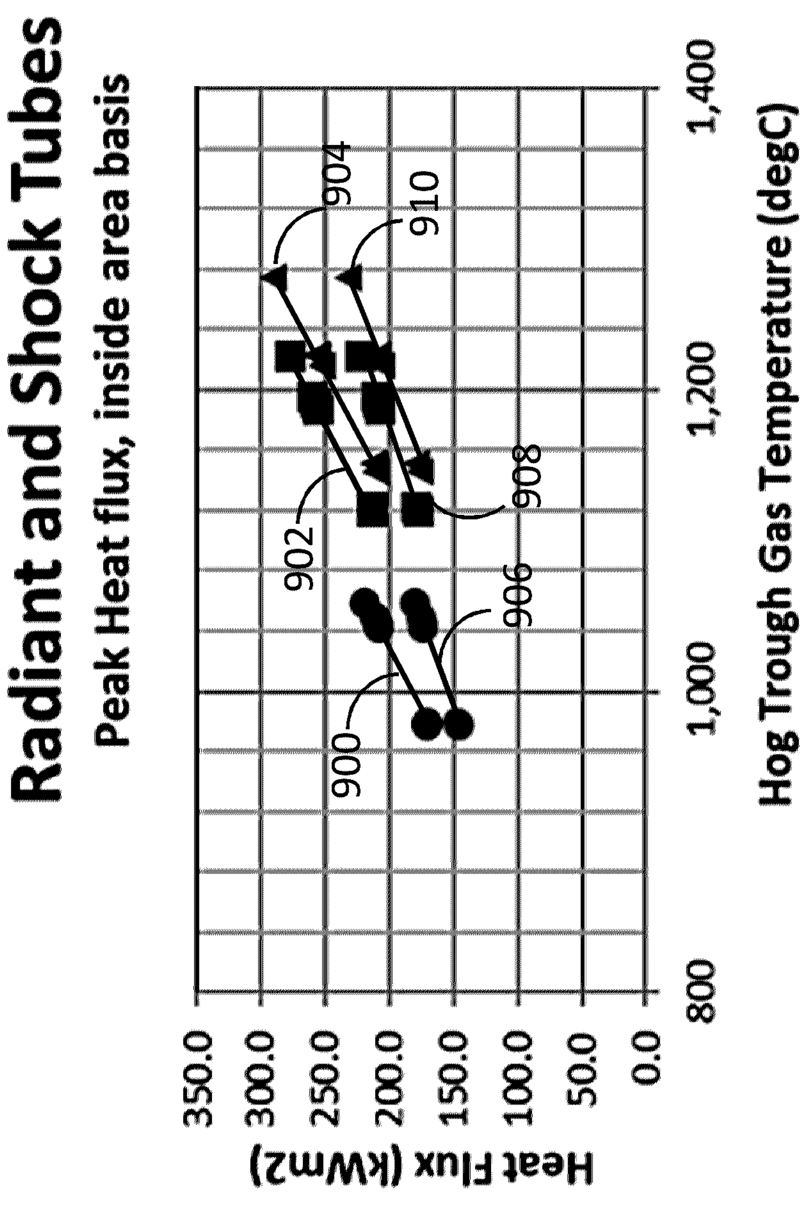

Radiant and Shock Tubes
Peak Heat flux, inside area basis
Heat Flux (kWm2)
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
800
1,000
1,200
1,400
Hog Trough Gas Temperature (degC)
900
902
904
906
908
910

FIG. 9

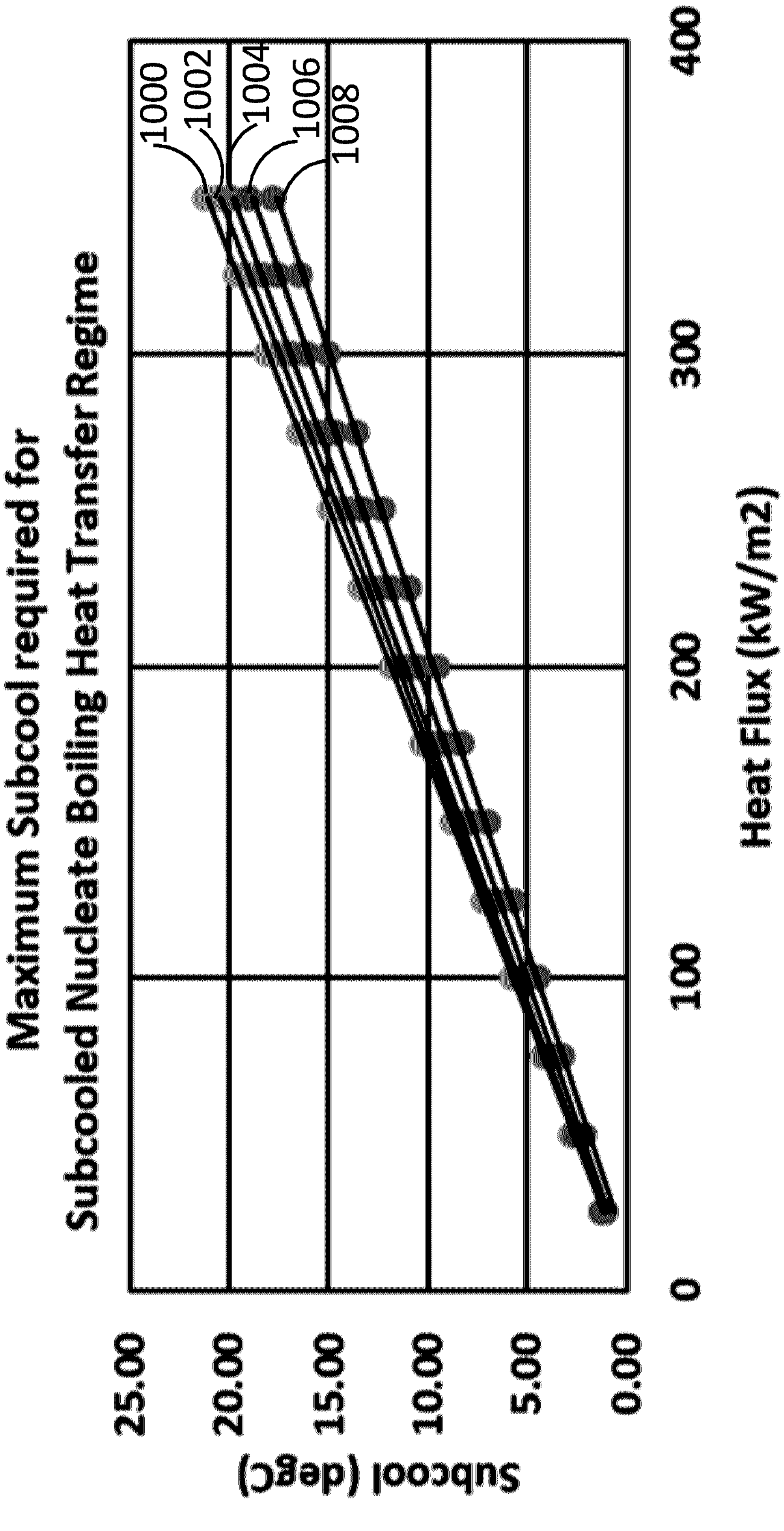
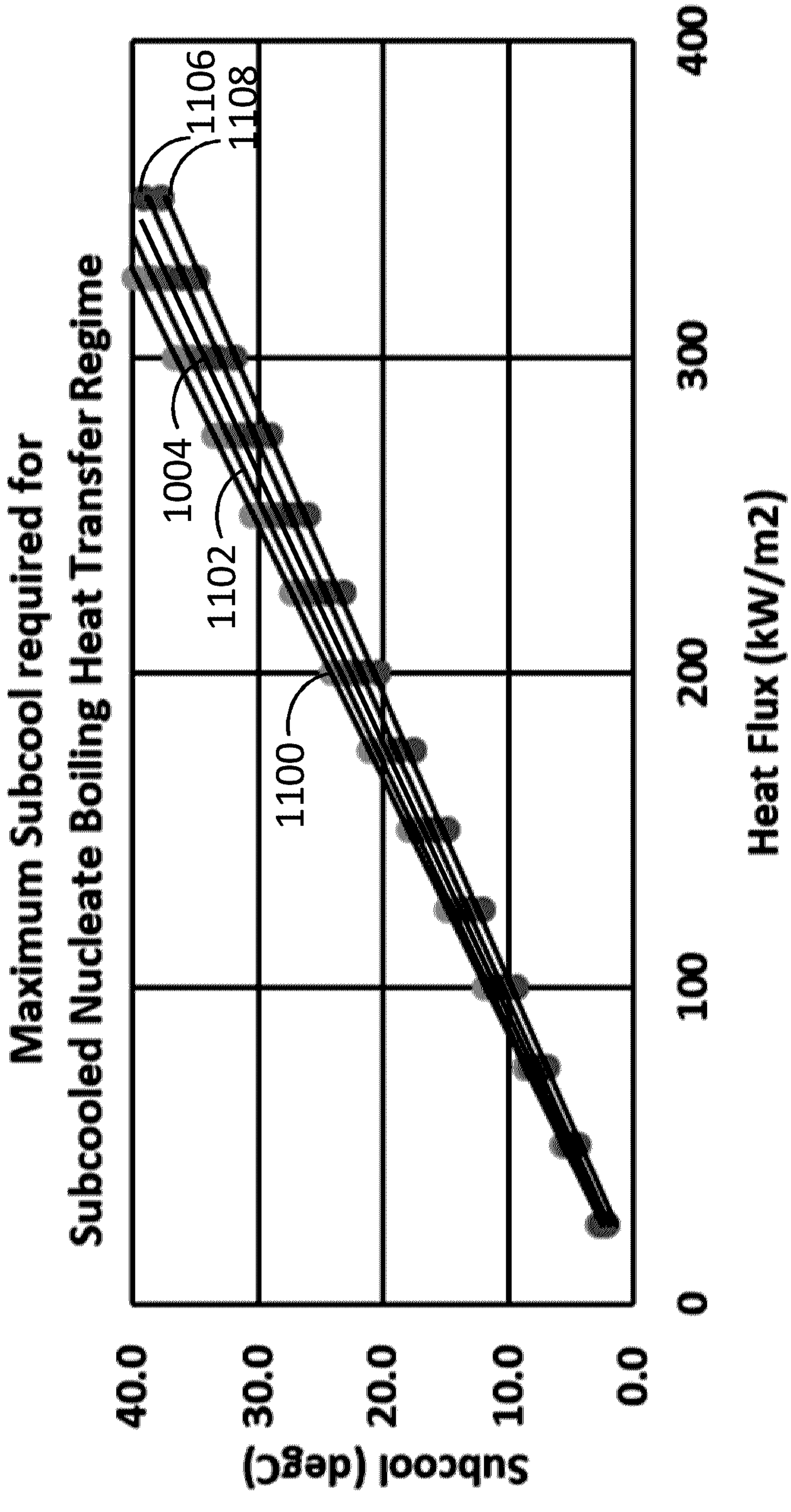
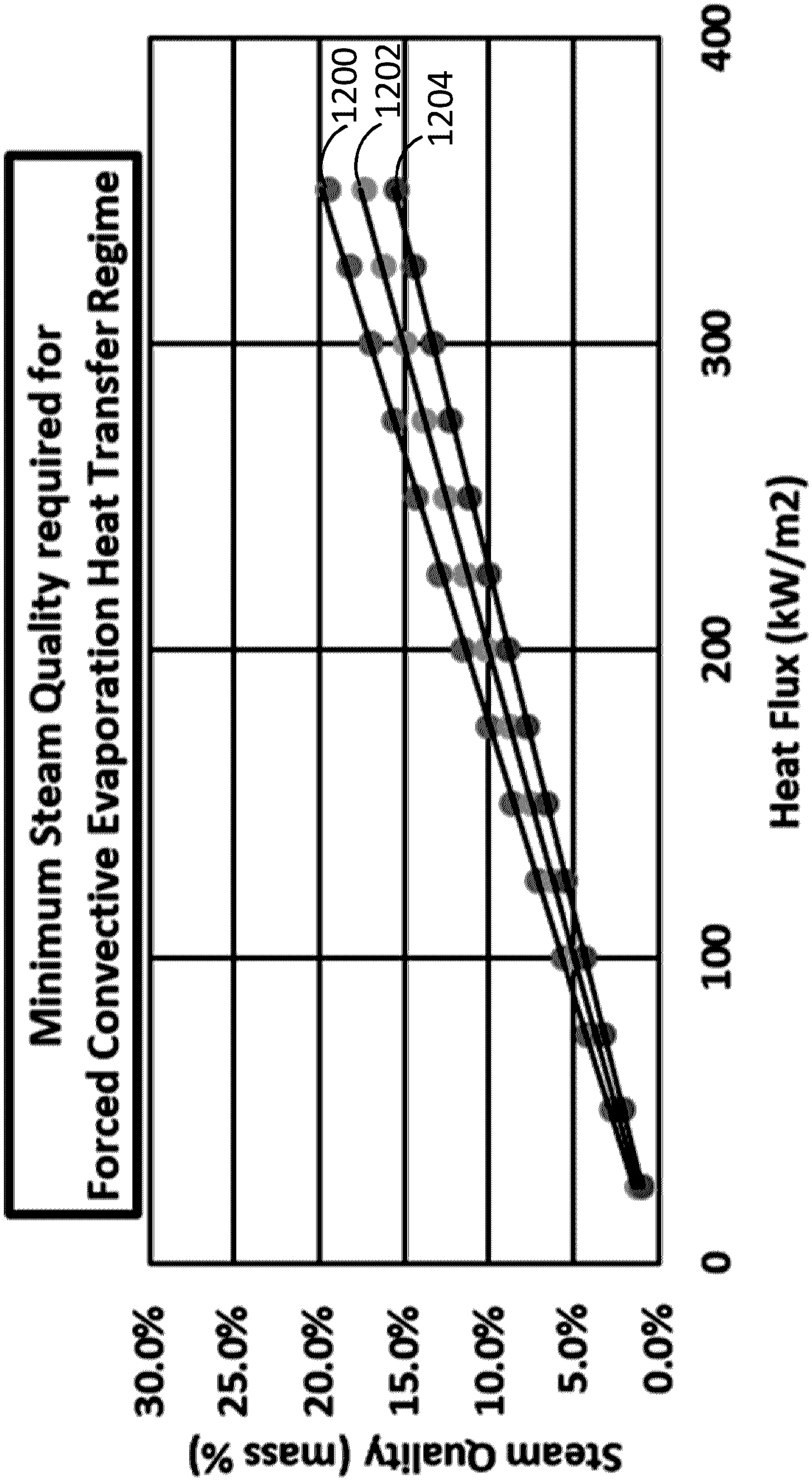

Maximum Subcool required for
Subcooled Nucleate Boiling Heat Transfer Regime
Subcool (degC)
25.00
20.00
15.00
10.00
5.00
0.00
0
100
200
300
400
Heat Flux (kW/m2)
1000
1002
1004
1006
1008

FIG. 10



Maximum Subcool required for
Subcooled Nucleate Boiling Heat Transfer Regime
Subcool (degC)
40.0
30.0
20.0
10.0
0.0
0
100
200
300
400
Heat Flux (kW/m2)
1100
1102
1004
1106
1108


FIG. 11



Minimum Steam Quality required for
Forced Convective Evaporation Heat Transfer Regime
Steam Quality (mass %)
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
0
100
200
300
400
Heat Flux (kW/m2)
1200
1202
1204


FIG. 12

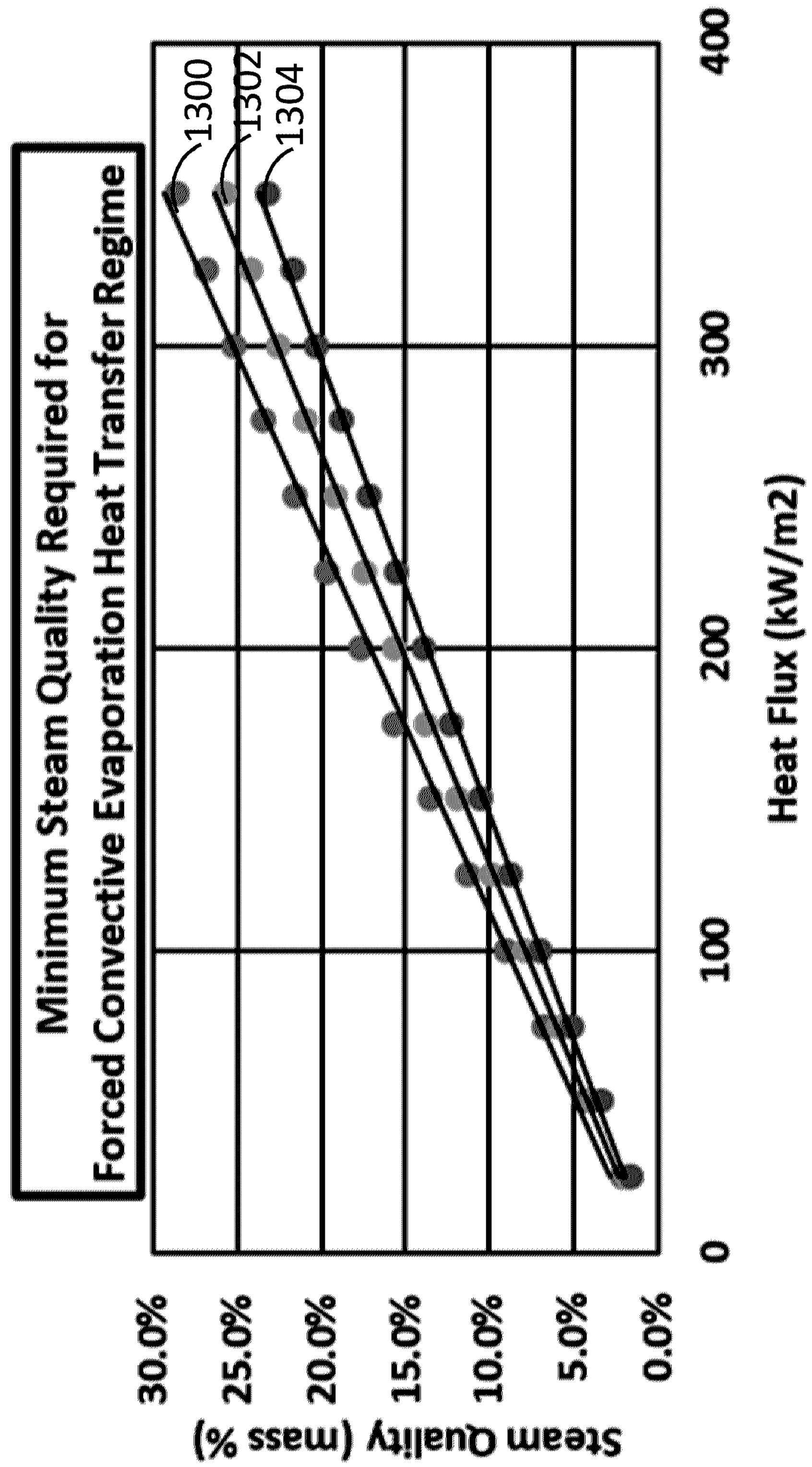

Minimum Steam Quality Required for
Forced Convective Evaporation Heat Transfer Regime
1300
1302
1304
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Steam Quality (mass %)
0
100
200
300
400
Heat Flux (kW/m2)

FIG. 13

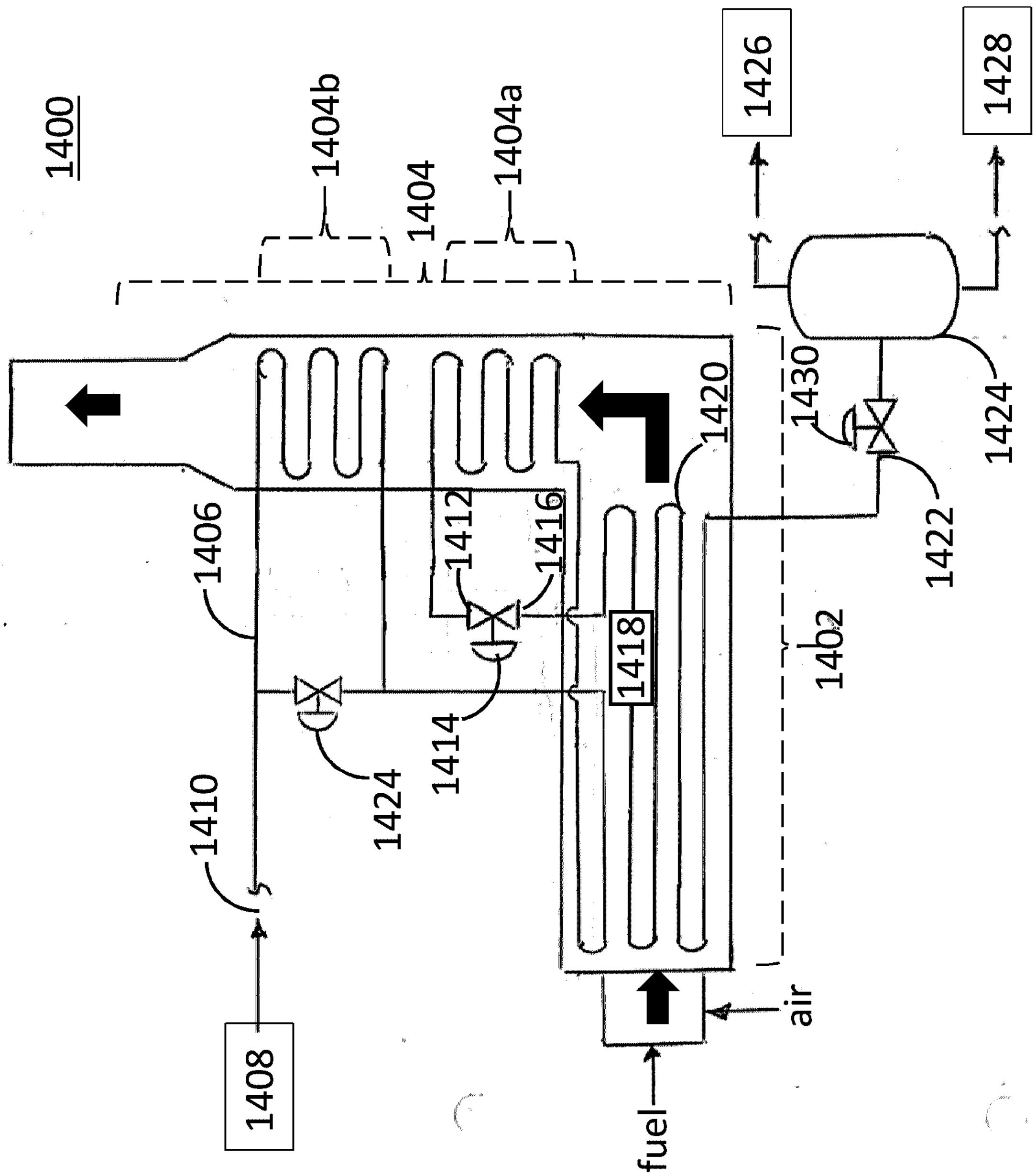



**FIG. 14**

Date Reçue/Date Received 2020-05-13

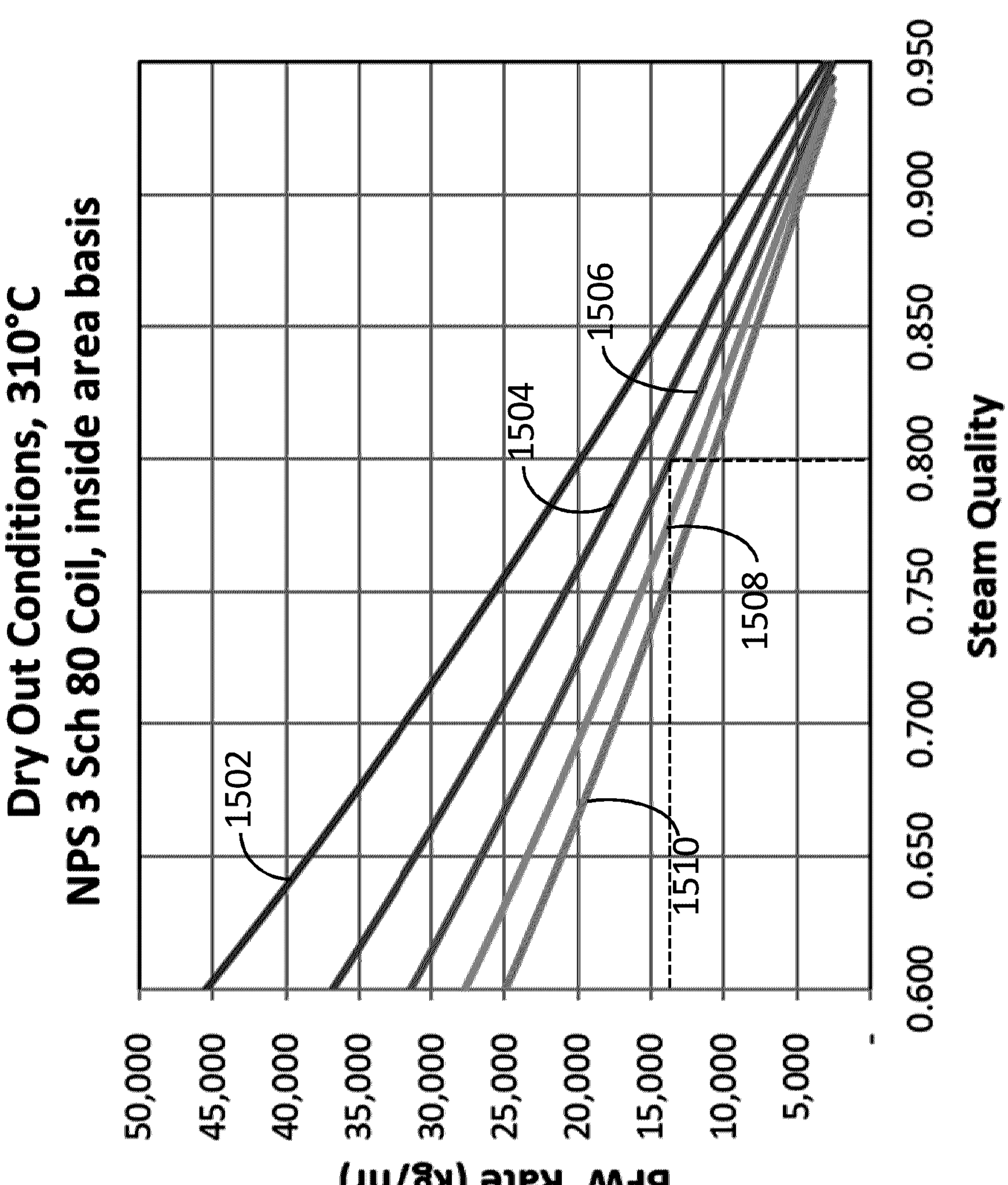



FIG. 15A

Date Reçue/Date Received 2020-05-13

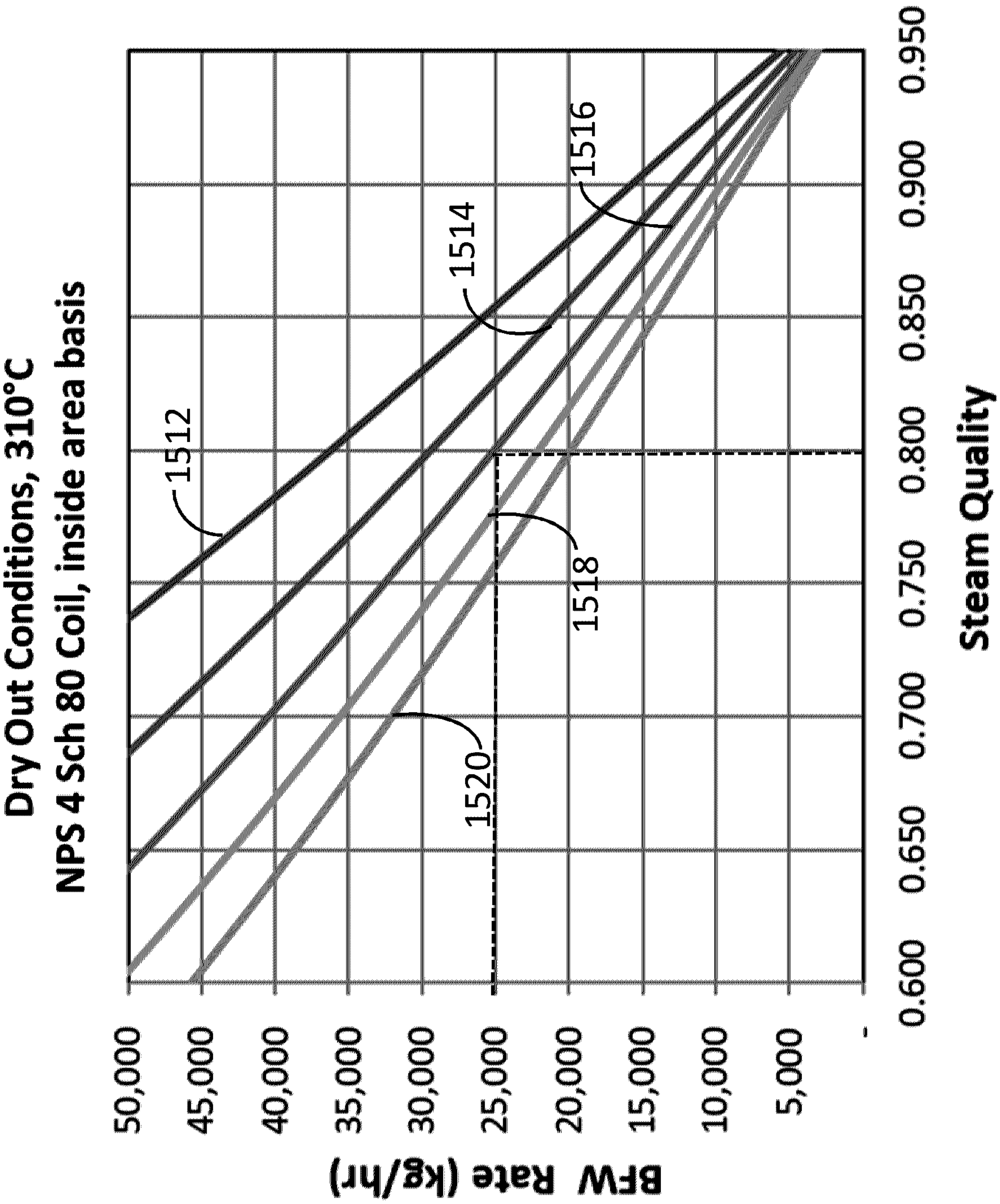

Dry Out Conditions, 310°C
NPS 4 Sch 80 Coil, inside area basis
BFW Rate (kg/hr)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
-
0.600
0.650
0.700
0.750
0.800
0.850
0.900
0.950
Steam Quality
1512
1514
1516
1518
1520

FIG. 15B

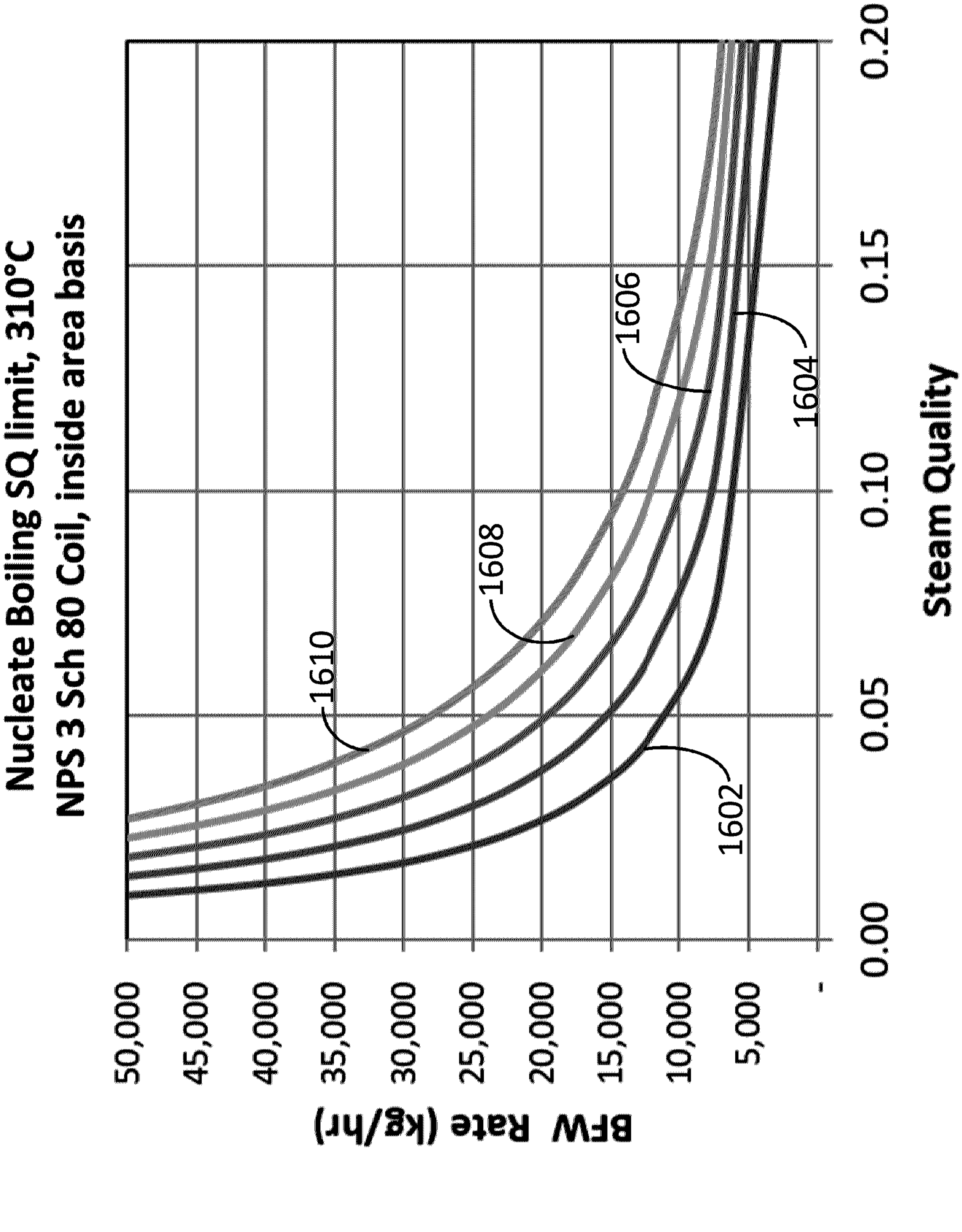



FIG. 16A

Date Reçue/Date Received 2020-05-13

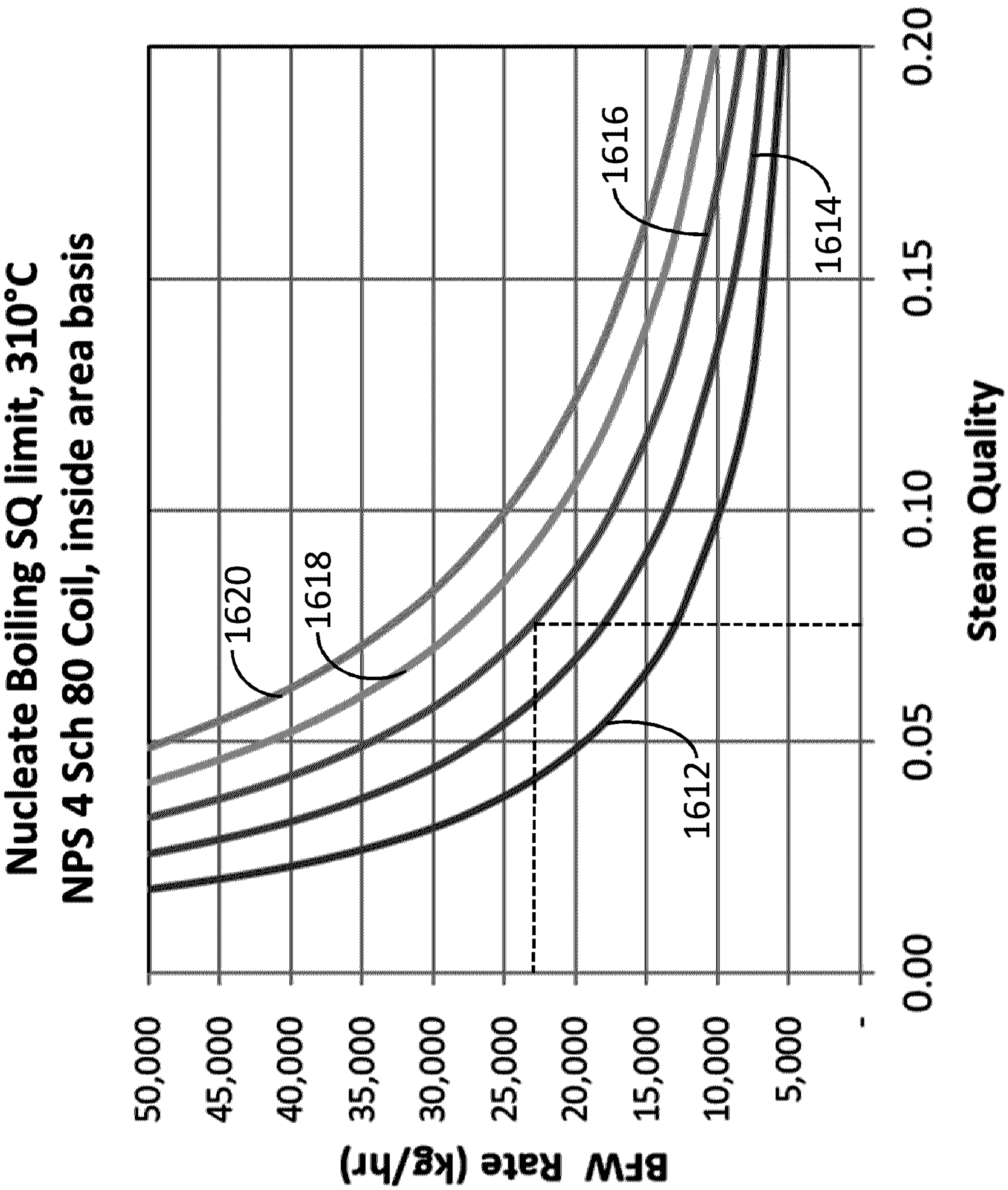

Nucleate Boiling SQ limit, 310°C
NPS 4 Sch 80 Coil, inside area basis
BFW Rate (kg/hr)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
-
0.00
0.05
0.10
0.15
0.20
Steam Quality
1612
1614
1616
1618
1620

FIG. 16B

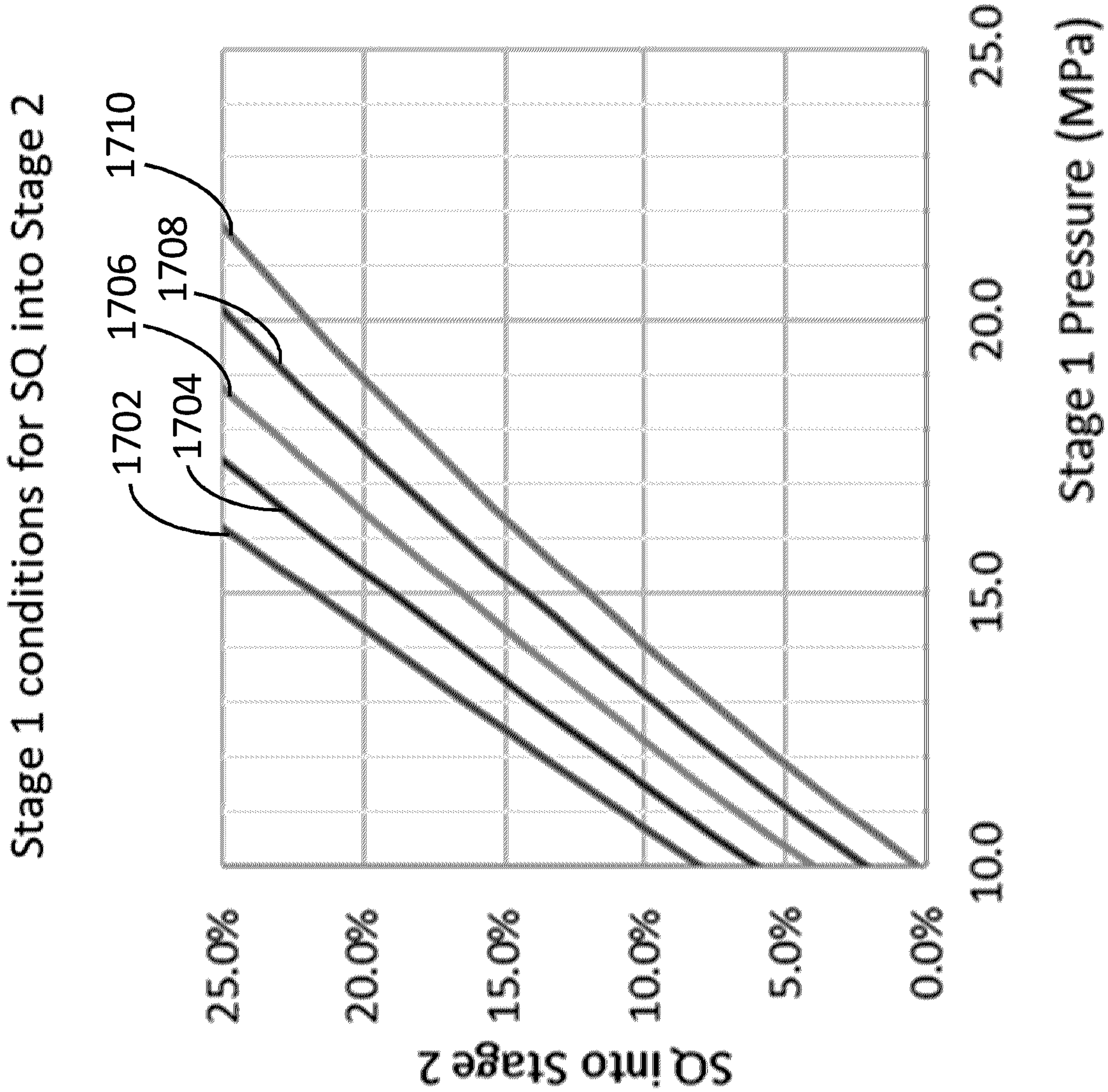
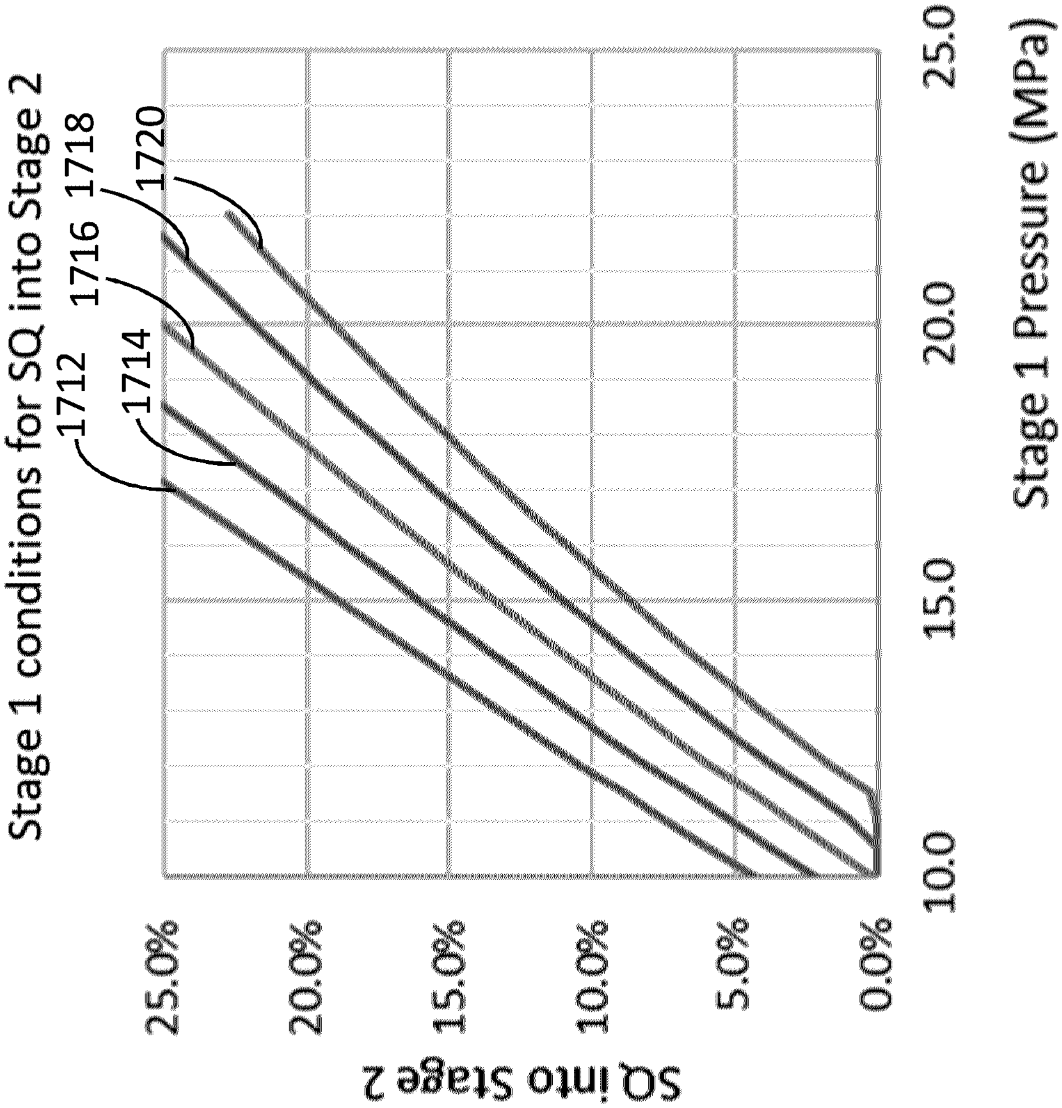

Stage 1 conditions for SQ into Stage 2
1702
1704
1706
1708
1710
SQ into Stage 2
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
10.0
15.0
20.0
25.0
Stage 1 Pressure (MPa)

**FIG. 17A**



Stage 1 conditions for SQ into Stage 2
1712
1714
1716
1718
1720
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
SQ into Stage 2
10.0
15.0
20.0
25.0
Stage 1 Pressure (MPa)


**FIG. 17B**

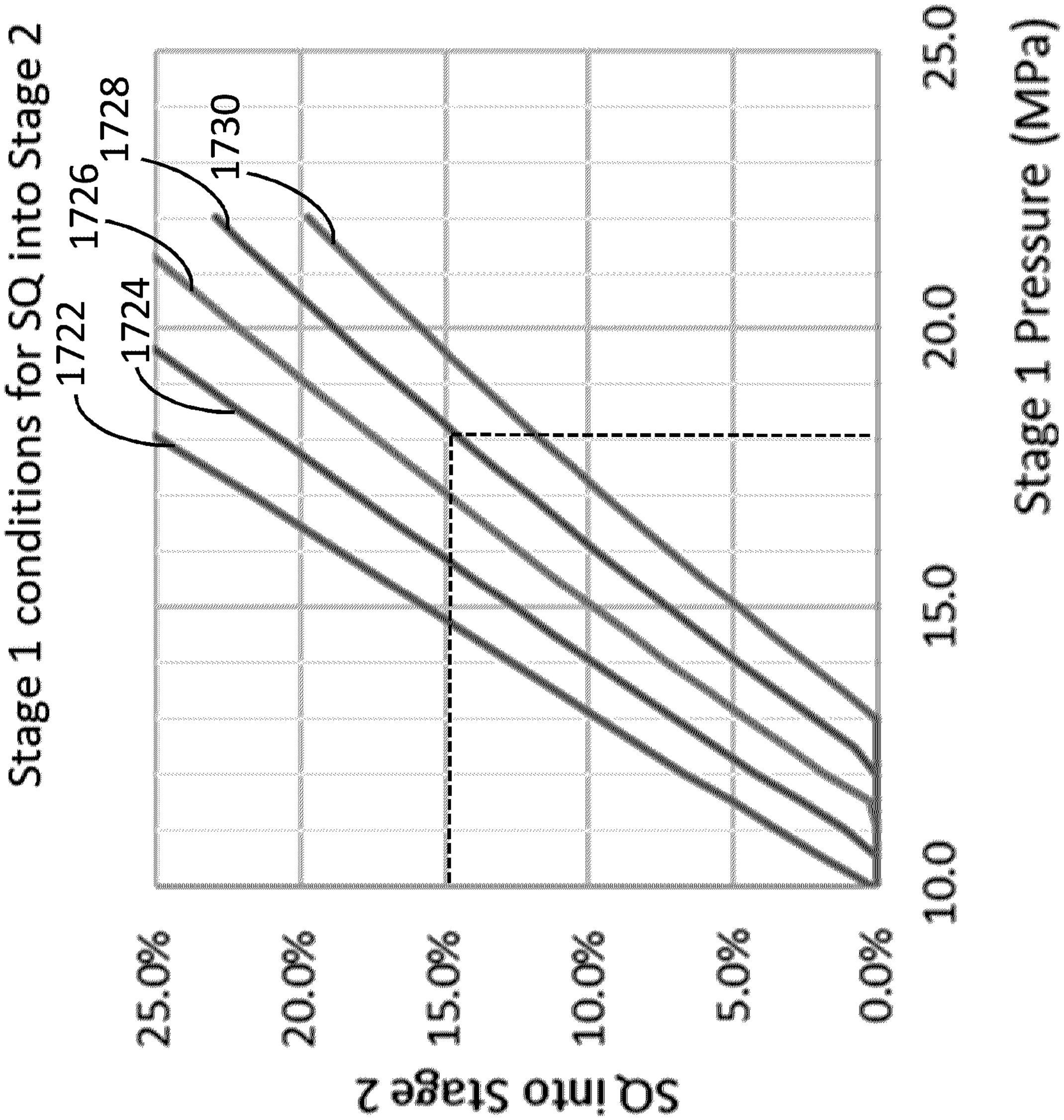

Stage 1 conditions for SQ into Stage 2
SQ into Stage 2
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
10.0
15.0
20.0
25.0
Stage 1 Pressure (MPa)
1722
1724
1726
1728
1730

**FIG. 17C**

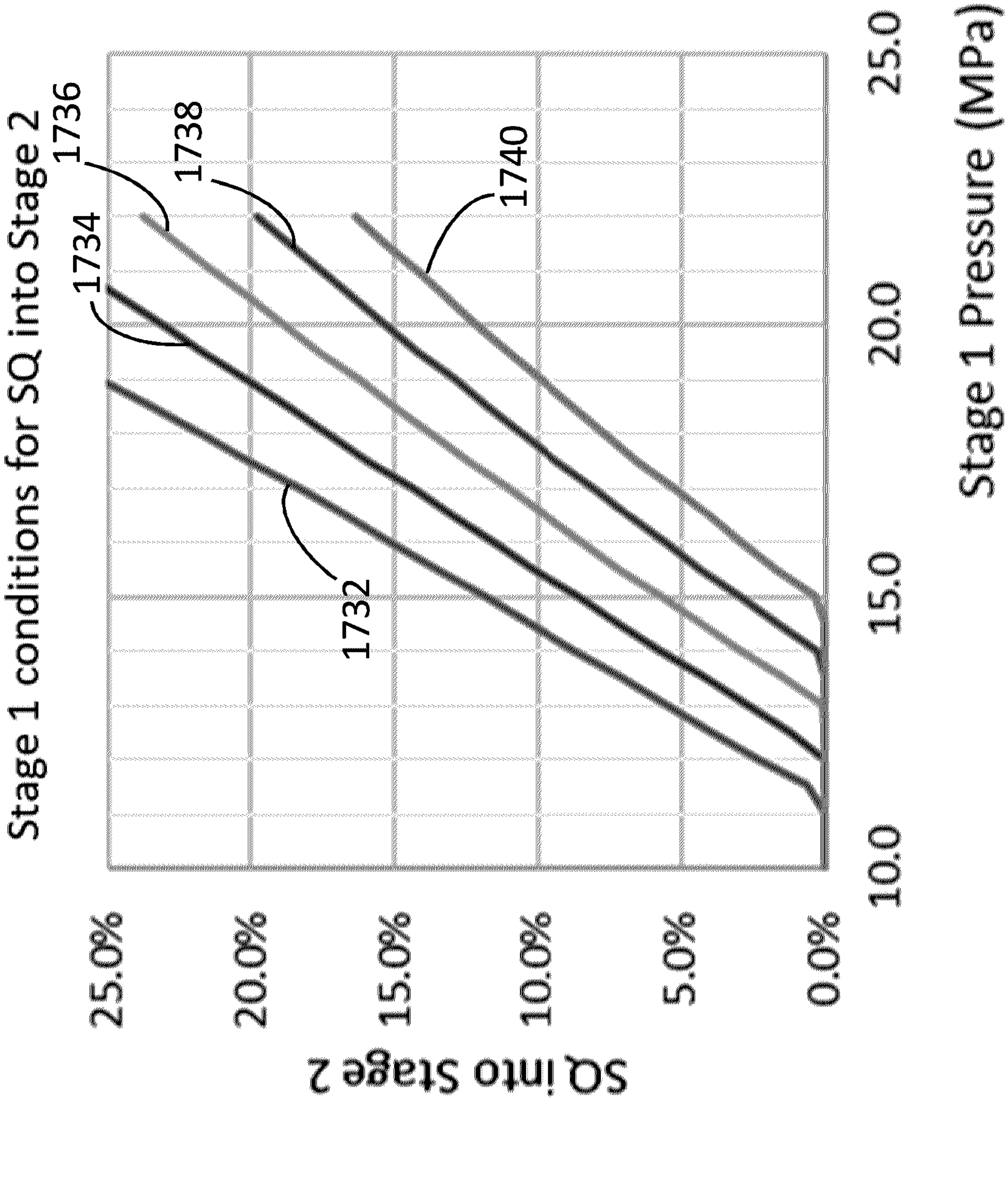

Stage 1 conditions for SQ into Stage 2
SQ into Stage 2
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
10.0
15.0
20.0
25.0
Stage 1 Pressure (MPa)
1732
1734
1736
1738
1740

FIG. 17D

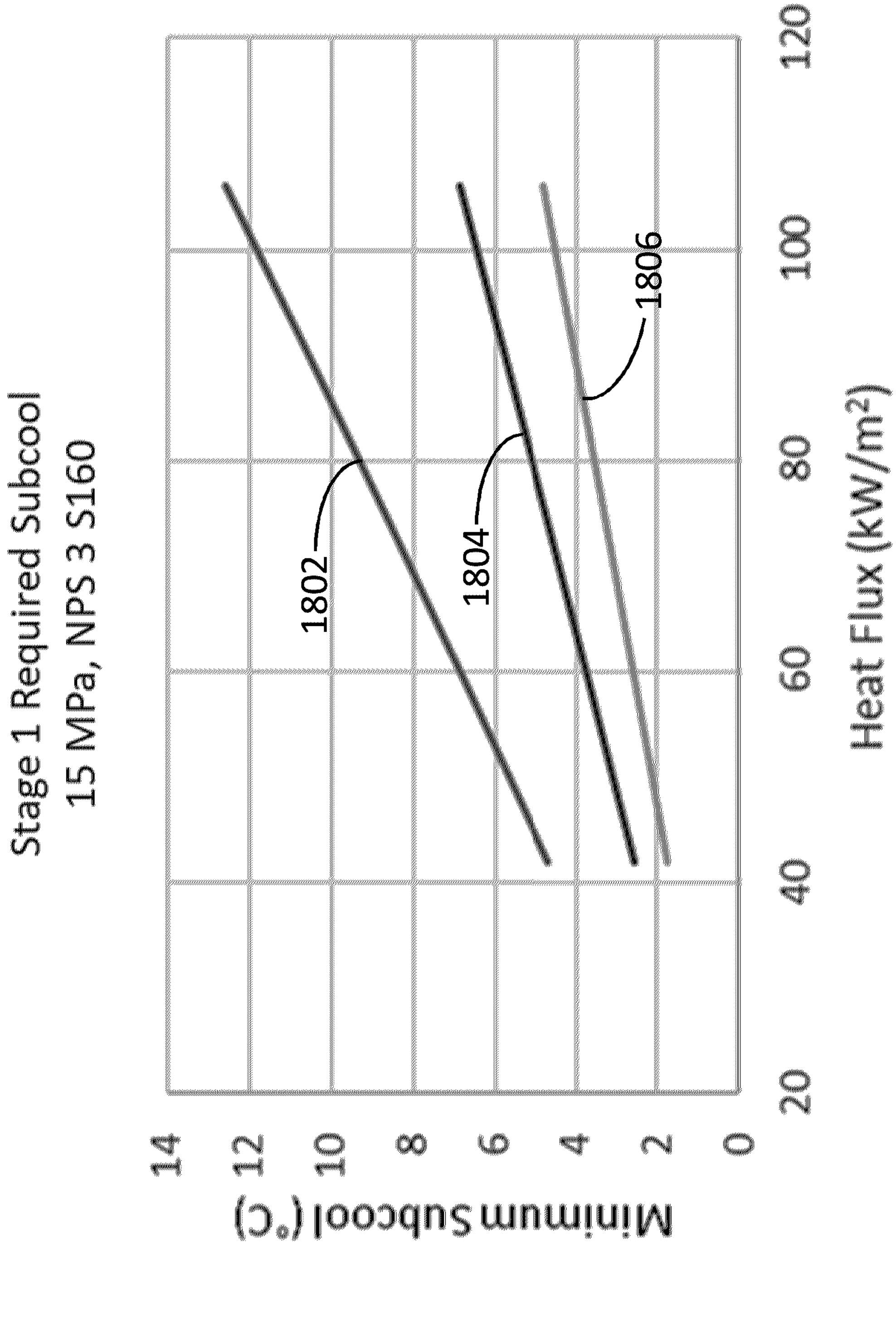



**FIG. 18A**

Date Reçue/Date Received 2020-05-13

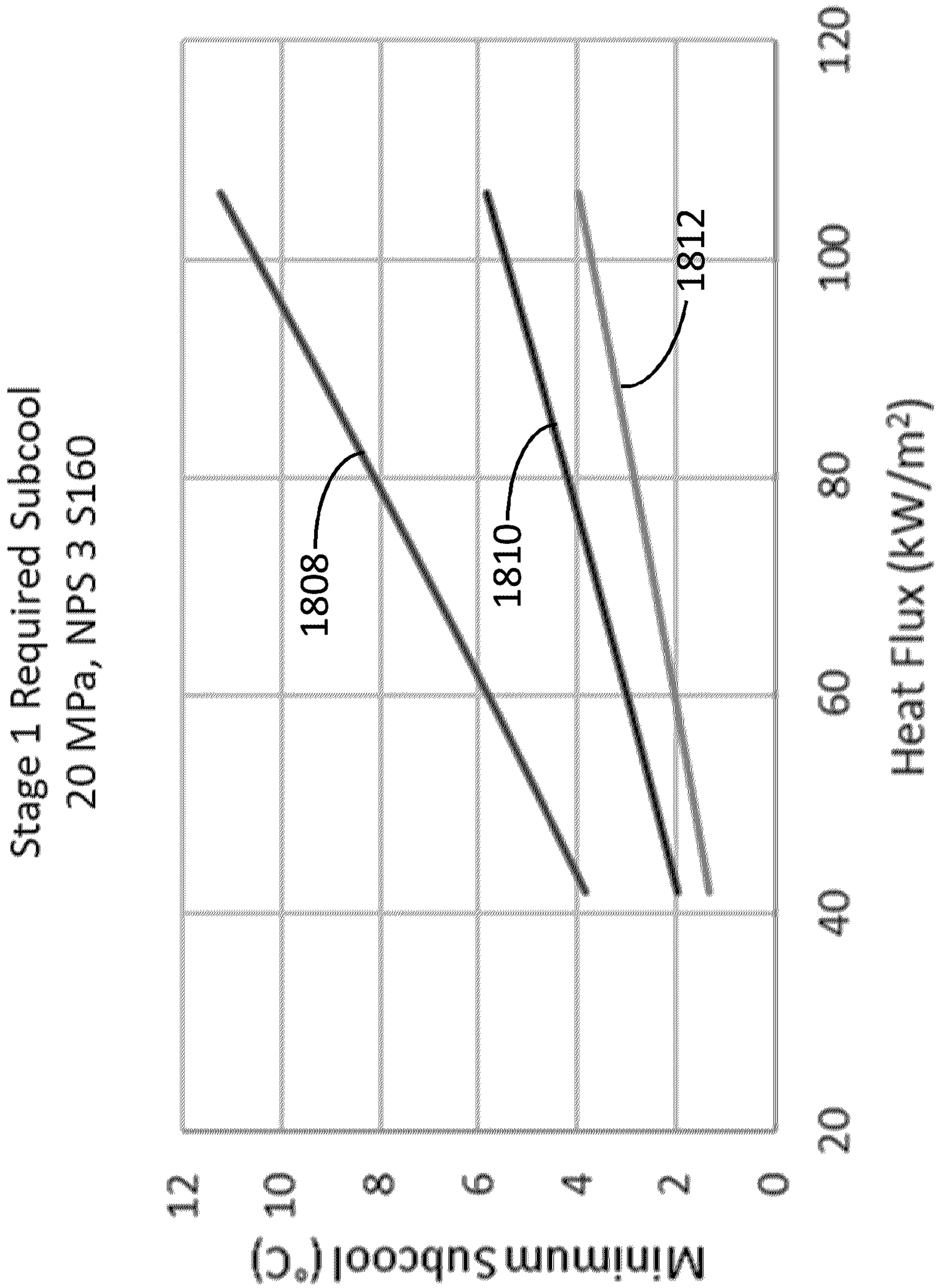

Stage 1 Required Subcool
20 MPa, NPS 3 S160
Minimum Subcool (°C)
0
2
4
6
8
10
12
20
40
60
80
100
120
Heat Flux (kW/m²)
1808
1810
1812

**FIG. 18B**

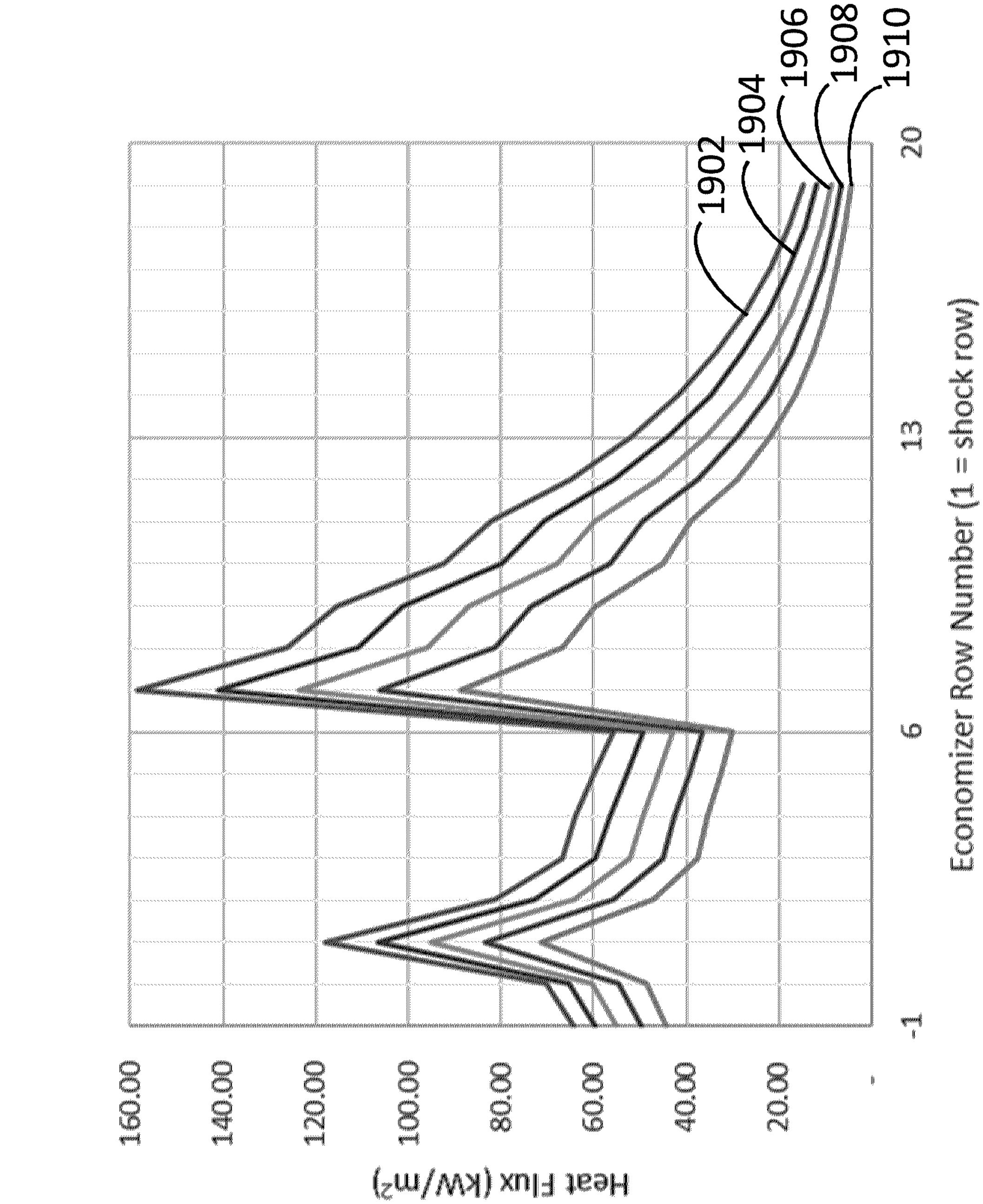

Heat Flux (kW/m²)
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
-
-1
6
13
20
Economizer Row Number (1 = shock row)
1902
1904
1906
1908
1910

**FIG. 19**

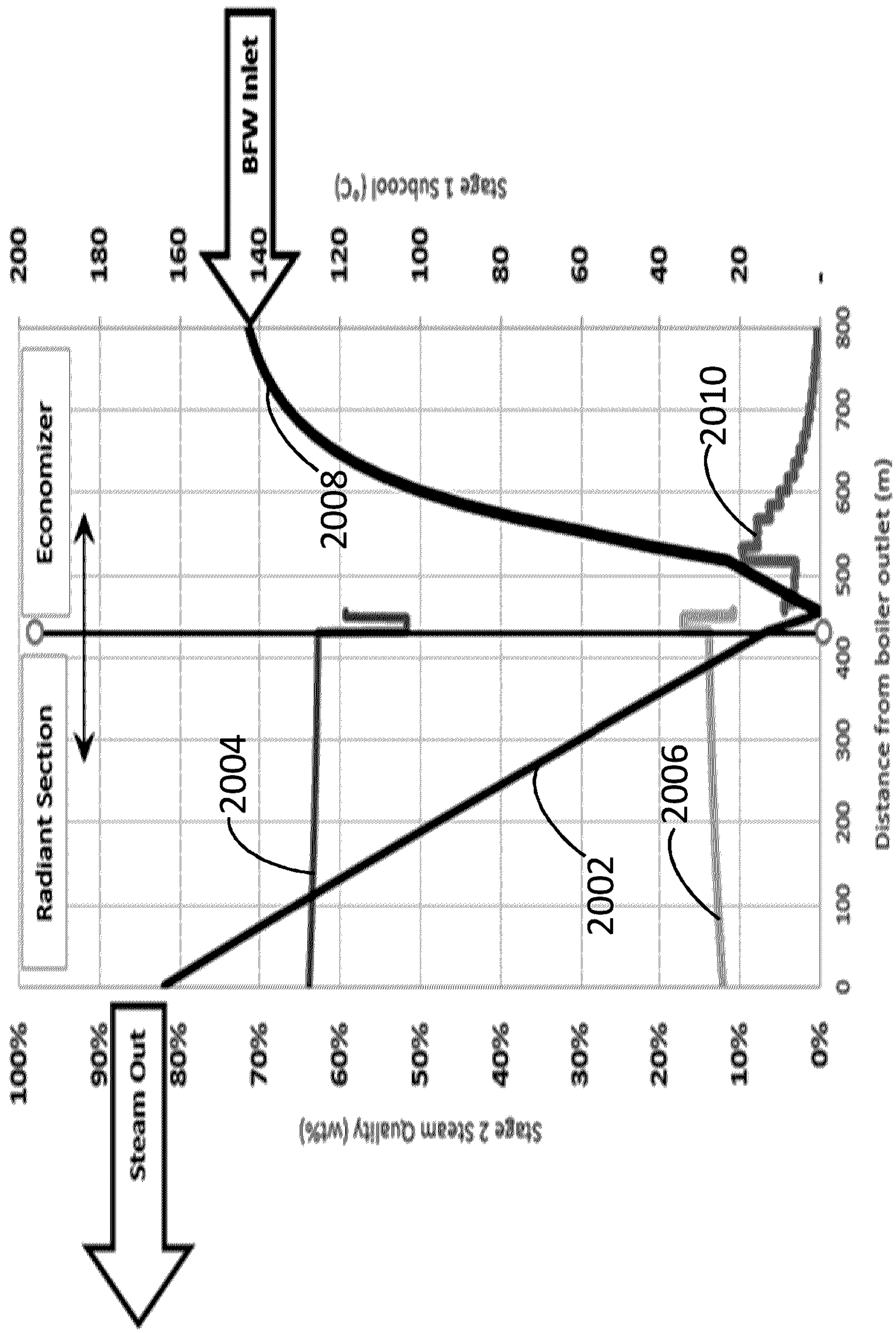
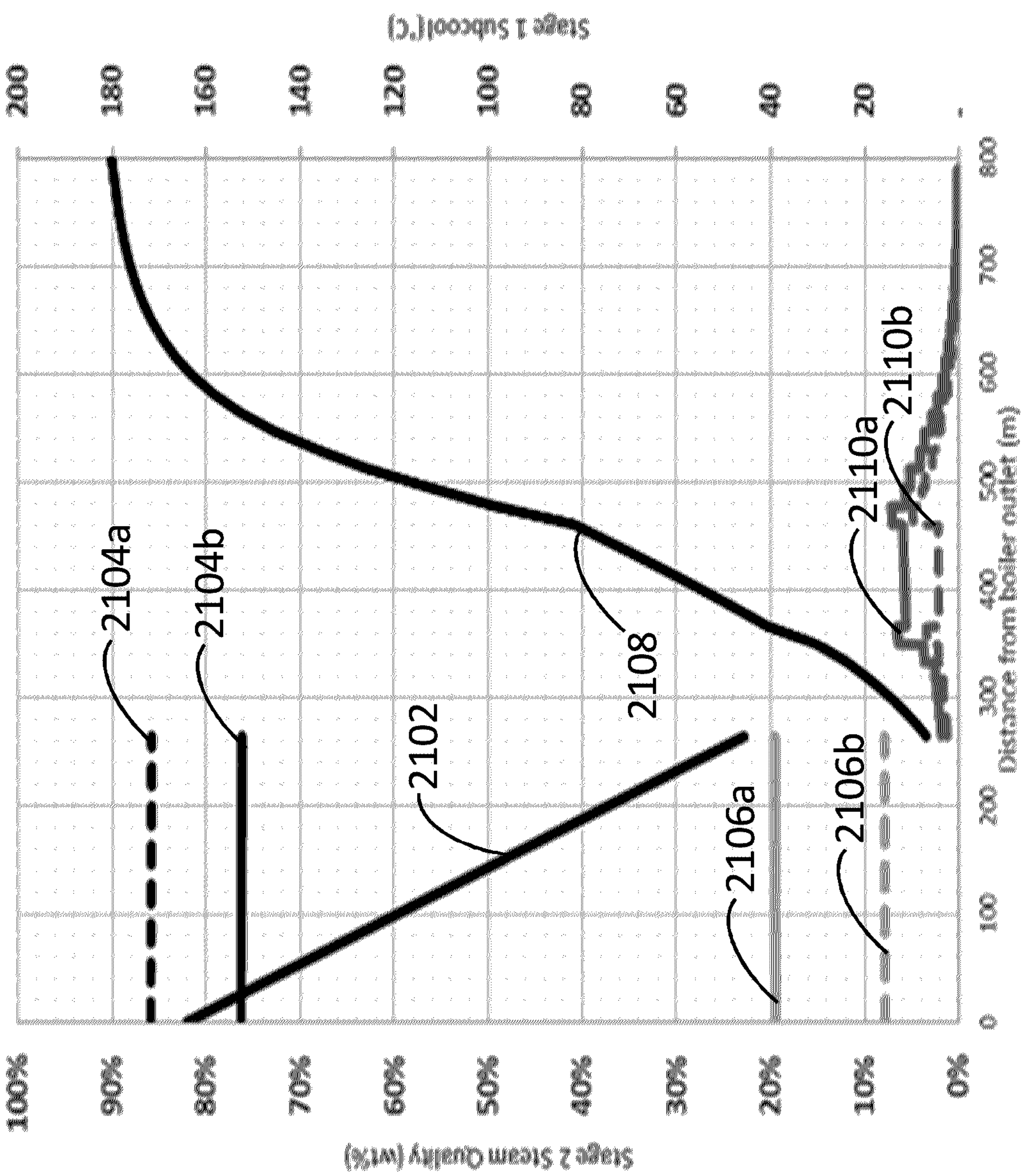
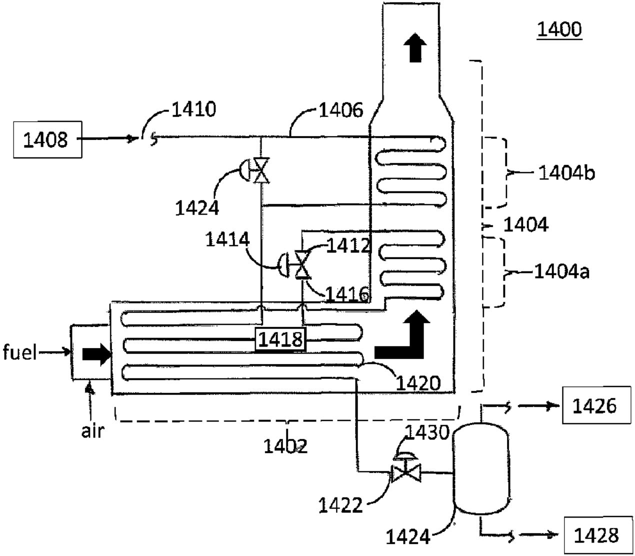

BFW Inlet
Stage 1 Subcool (°C)
Steam Out
Stage 2 Steam Quality (wt%)
Radiant Section
Economizer
Distance from boiler outlet (m)
2002
2004
2006
2008
2010

FIG. 20



Stage 2 Steam Quality (wt%)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Stage 1 Subcool(°C)
20
40
60
80
100
120
140
160
180
200
Distance from boiler outlet (m)
0
100
200
300
400
500
600
700
800
2102
2104a
2104b
2106a
2106b
2108
2110a
2110b


**FIG. 21**



1400
1410
1406
1408
1404b
1424
1404
1414
1412
1404a
1416
1418
fuel
1420
1426
air
1430
1402
1422
1424
1428