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(71) Applicant: **THE UNIVERSITY OF SYDNEY** [AU/AU]; c/o Davies Collison Cave, Level 14, 255 Elizabeth Street, Sydney, New South Wales 2000 (AU).

(72) Inventor: **ABBAS, Ali**; Unit 5, 5-7 Preddys Road, Bexley, New South Wales 2207 (AU).

(74) Agent: **DAVIES COLLISON CAVE**; Level 14, 255 Elizabeth Street, Sydney, New South Wales 2000 (AU).

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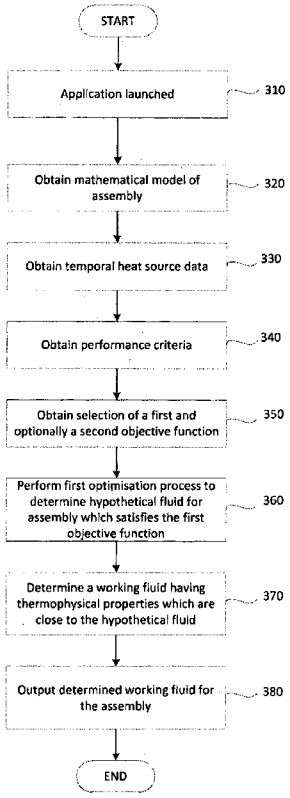


FIGURE 3

(57) Abstract: A method, processing system, computer readable medium and system for determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink. In one aspect, the method includes the following steps : providing a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid; determining one or more objective functions associated with the mathematical model of the assembly; and manipulating a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

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A METHOD OF DETERMINING THE THERMOPHYSICAL PROPERTIES OF A WORKING FLUID

The present invention relates to a method of determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink.

Background

The following background of the present invention includes a discussion on working fluids used in assemblies including heat pipes. However the present invention may also apply to other assemblies that include a working fluid that facilitates the transfer of thermal energy between a heat source and a heat sink, such as for example heat pump assemblies.

Heat pipes are reliable and efficient heat transfer devices. Many types of heat pipes have been developed for a wide variety of applications ranging from very small micro heat pipes for cooling microchips to heat pipes several meters in length suitable for long distance heat transfer. Heat pipes generally work based on phase change of a working fluid, which evaporates at one end and condenses at another within a closed pipe. Based on this phenomenon, many designs of heat pipes have been developed, such as classical thermosiphons or wickless heat pipes, wrapped screen heat pipes, artery heat pipes, grooved heat pipes, capillary pumped heat pipes, pulsating heat pipes, and micro heat pipes.

Research in this field continues to pursue novel types of heat pipes to suit new applications and to increase the performance of existing heat pipe designs. Micro grooved heat pipes represent a new heat pipe design concept. Interest in this type of heat pipe arises from its flexibility in design, generalization of the working fluid behaviour, downward scalability, relatively high mechanical resistance of wick structure, lower fabrication cost, and lower dependency on gravity.

Heat pipes, like any other devices, have different aspects of performance. Most of the previous research in this area has focused on heat transfer limits and hydrodynamics of heat pipes' operation which are very important in terms of determining maximum heat transfer capability of a heat pipe. The hydrodynamics phenomenon of more conventional heat pipes is generally well understood. Theoretical models have been developed to investigate the effect of geometrical or working fluid design parameters. However, the effect of hydrodynamics and working fluid properties on thermal resistance of heat pipes is not well understood.

Thermal resistance is the most important parameter that reflects the performance of a heat pipe in operation within given heat transfer limits. It is highly desirable to decrease the thermal resistance of a heat pipe along with increasing the heat transfer limits.

The present invention seeks to provide a method of determining the most suitable thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink.

Summary

In a first aspect there is provided a method of determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system:

performing a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein one or more thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

performing a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from a known fluid list, wherein one or more thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the

working fluid for the assembly.

In certain embodiments, the step of the processing system manipulating the thermophysical properties of the fluid mixture includes manipulating:

a number of fluids selected from the known fluid list to form the fluid mixture;

a selection of fluids from the known fluid list to form the fluid mixture; and

a proportion of each selected fluid in the fluid mixture.

In certain embodiments, the mathematical model is dependent upon:

performance criteria; and

temporal heat source data.

In certain embodiments, the processing system obtains at least one of the performance criteria and the temporal heat source data at least partially based upon input data from a user.

In certain embodiments, the method includes the processing system manipulating the thermophysical properties of the modelled working fluid within a range of thermophysical properties defined by the fluids in the known fluid list.

In certain embodiments, the method includes the processing system minimising the discrepancy between the thermophysical properties of the fluid mixture and the hypothetical fluid by manipulating the thermophysical properties of the fluid mixture during the second optimisation process, wherein the fluid mixture having the thermophysical properties which result in a minimalised discrepancy is determined by the processing system as the working fluid.

In certain embodiments, the method includes the processing system receiving input data indicative of a selection of the mathematical model from a library of mathematical models for a plurality of assemblies.

In certain embodiments, at least one of the first optimisation process and the second optimisation process is performed using one of the following optimisation algorithms:

genetic algorithm; and

pattern search.

In certain embodiments, the one or more thermophysical properties are selected from vapour and/or liquid phase thermophysical properties.

In certain embodiments, the thermophysical properties are selected from: thermal conductivity, viscosity, surface tension, latent heat of evaporation, density, specific heat capacity, vapour pressure, and isentropic expansion factor/heat capacity ratio.

In certain embodiments, the assembly involving the transfer of thermal energy between a heat source and a heat sink is selected from a heat pump, a heat pipe or an apparatus including one or more heat pumps and/or heat pipes.

In certain embodiments, the assembly is used in an application including: heat pumps including solar heat pumps; heat pipes; solar thermal including solar water heaters, solar cooling and solar ovens; chipset cooling including CPU and GPUs; permafrost cooling; cooking; ventilation heat recovery in air condition systems; refrigeration; cooling and dehumidification in HVAC; heat pipe heat exchangers; spacecraft thermal control; and, thermal transfer in energy storage including batteries and thermal storage fluids.

In certain embodiments, the first objective function is one of: an economic objective function, a techno-economic objective function, and a technical objective function.

In certain embodiments, the first objective function is selected from: minimizing the operating cost of the assembly, minimizing the capital cost of the assembly, the net present value and combinations thereof.

In certain embodiments, the mathematical model of the assembly includes the effect of hydrodynamics of the modelled working fluid on one or more of the following: the thermal resistance of the assembly; the critical heat flux of the assembly; and the thermal failure ratio of a built-in heat pipe/heat pump in the assembly.

In certain embodiments, the mathematical model of the assembly includes a reduction in the dimension of the domain of the mathematical model through the use of dimensionless numbers.

In certain embodiments, the known fluid list includes one or more of the following: acetone, 2,2-dimethyl propane, isobutene, n-butane, 2-methyl butane, n-pentane, n-hexane, n-heptane, cyclo-pentane, cyclo-hexane, benzene, chloroform, acetone, chlorine, ammonia, water, 1-pentanol, iso-butanol, acetadol, methanol, ethanol, isopropyl alcohol, 3,3-dimethyl-1-butene, di-chloro mono-flouro methane, ethylene oxide and propylene oxide.

In certain embodiments, the method includes providing the assembly using the determined working fluid.

In a second aspect there is provided a processing system for determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

perform a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

perform a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from an known fluid list, wherein thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the working

fluid for the assembly.

In certain embodiments, the processing system is configured to perform the method of the first aspect.

In a third aspect there is provided a system for providing an assembly including a working fluid for transferring thermal energy between a heat source and a heat sink, wherein the system includes:

the processing system according to the second aspect; and

a plant to provide the assembly including the working fluid.

In a fourth aspect there is provided a computer readable medium for configuring a processing system to determine a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer readable medium includes executable instructions which when executed configures the processing system to:

perform a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

perform a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from an known fluid list, wherein thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the working fluid for the assembly.

In certain embodiments, the computer readable medium configures the processing system to perform the method of the first aspect.

In a fifth aspect there is provided a method of determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system performing steps of:

performing an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized;

comparing the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

selecting, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

In a sixth aspect there is provided a processing system for determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

perform an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized;

compare the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

select, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

In a seventh aspect there is provided a computer readable medium for configuring a processing system to determine a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer

readable medium includes executable instructions which when executed configures the processing system to:

perform an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized;

compare the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

select, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

In an eighth aspect method of determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, the method including the following steps:

providing a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determining one or more objective functions associated with the mathematical model of the assembly; and

manipulating a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

In certain embodiments, the one or more thermophysical properties of the working fluid are selected from vapour and/or liquid phase thermophysical properties.

In certain embodiments, the thermophysical properties are selected from: thermal conductivity, viscosity, surface tension, latent heat of evaporation, density, specific heat capacity, vapour pressure, and isentropic expansion factor/heat capacity ratio.

In certain embodiments, the assembly involving the transfer of thermal energy between a heat source and a heat sink is selected from a heat pump, a heat pipe or an apparatus including one or more heat pumps and/or heat pipes.

In certain embodiments, the assembly involving the transfer of thermal energy between a heat source and a heat sink is used in an application including: heat pumps including solar heat pumps; heat pipes; solar thermal including solar water heaters, solar cooling and solar ovens; chipset cooling including CPU and GPUs; permafrost cooling; cooking; ventilation heat recovery in air condition systems; refrigeration; cooling and dehumidification in HVAC; heat pipe heat exchangers; spacecraft thermal control; and, thermal transfer in energy storage including batteries and thermal storage fluids.

In certain embodiments, the objective function associated with the mathematical model includes one or more of the following: economic objective functions, techno-economic objective functions, and/or technical objective functions.

In certain embodiments, the objective function is selected from: minimizing the operating cost of the assembly, minimizing the capital cost of the assembly, the net present value and combinations thereof.

In certain embodiments, the mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid includes the effect of hydrodynamics of the working fluid on one or more of the following: the thermal resistance of the assembly; the critical heat flux of the assembly; and the thermal failure ratio of the built-in heat pipe/heat pump in the assembly.

In certain embodiments, the mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid includes a reduction in the dimension of the domain of the mathematical model through the use of dimensionless numbers.

In certain embodiments, the further step of comparing the one or more thermophysical properties of the working fluid which meet the objective function against a data set of one or more thermophysical properties of one or more known working fluids.

In certain embodiments, the known working fluids include one or more of the following: acetone, 2,2-dimethyl propane, isobutene, n-butane, 2-methyl butane, n-pentane, n-hexane, n-heptane, cyclo-pentane, cyclo-hexane, benzene, chloroform, acetone, chlorine, ammonia, water, 1-pentanol, iso-butanol, acetadol, methanol, ethanol, isopropyl alcohol, 3,3-dimethyl-1-butene, di-chloro mono-flouro methane, ethylene oxide and propylene oxide

In certain embodiments, wherein the method includes the subsequent step of selecting a working fluid from the one or more known working fluids which includes one or more thermophysical properties that match closest to the one or more thermophysical properties of the working fluid which meet the objective function.

In certain embodiments, the method includes the subsequent step of selecting a mixture of the one or more known working fluids which includes one or more thermophysical properties that match closest to the one or more thermophysical properties of the working fluid which meet the objection function.

In a ninth aspect there is provided a method of determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system perform the steps of:

providing a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determining one or more objective functions associated with the mathematical model of the assembly; and

manipulating a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby

determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

In a tenth aspect there is provided a processing system for determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

provide a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determine one or more objective functions associated with the mathematical model of the assembly; and

manipulate a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

In an eleventh aspect there is provided a computer readable medium for configuring a processing system to determine one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer readable medium includes executable instructions for configuring the processing system to:

provide a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determine one or more objective functions associated with the mathematical model of the assembly; and

manipulate a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

Other aspects and embodiments will be appreciated throughout the detailed description and examples.

Brief Description Of Figures

Example embodiments should become apparent from the following description, which is given by way of example only, of at least one preferred but non-limiting embodiment, described in connection with the accompanying figures.

Figure 1 illustrates a functional block diagram of an example processing system that can be utilised to embody or give effect to a particular embodiment;

Figure 2 illustrates an example network infrastructure that can be utilised to embody or give effect to a particular embodiment;

Figure 3 is flowchart representing a method performed by a processing system for determining a working fluid optimised for an assembly;

Figure 4 is a schematic diagram of an example heat pipe with axial swallow-tailed microgrooves;

Figure 5 is a schematic of heat flow paths and thermal resistances for the heat pipe of Figure 4;

Figure 6 is a graphical representation of a comparison of calculated pressure distribution ($T = 27^{\circ}C$ and $Q_{in} = 100W$ $Q_{in} = 212.3W$) determined using the mathematical model of example 1 with Chen *et al.*;

Figure 7 is a graphical representation of a comparison of a calculated meniscus radius ($T = 27^{\circ}C$ and $Q_{in} = 212.3W$) determined using the mathematical model of example 1 with Chen *et al.*;

Figure 8 is a graphical representation of a comparison of calculated critical heat flux vs. temperature determined using the mathematical model of example 1 with Chen *et al.*;

Figure 9 is a graphical representation of pressure distribution, using the mathematical model of example 1, of different working fluids along the heat pipe ($T = 60^{\circ}C$ and $Q_{in} = 50W$) of Figure 4;

Figure 10 is a graphical representation of meniscus radius distribution, using the mathematical model of example 1, of different working fluids along the heat pipe ($T = 60^{\circ}C$ and $Q_{in} = 50W$) of Figure 4;

Figure 11 is a graphical representation of the pressure drop index for vapour and liquid phase of different working fluids in different temperatures using the mathematical model of example 1;

Figure 12 is a graphical representation of heat vs. temperature drop using the mathematical model of example 1;

Figure 13 is a graphical representation of thermal resistance vs. working temperature for different working fluids using the mathematical model of example 1;

Figure 14 is a graphical representation of critical heat flux vs. working temperature for different working fluids using the mathematical model of example 1;

Figure 15 is a graphical representation of the figure of merit for different working fluids at different working temperatures using the mathematical model of example 1;

Figure 16 is a graphical representation of a 1-D sensitivity analysis for viscosity, surface tension, thermal conductivity, latent heat, and liquid density of water ($T = 50^{\circ}C$ and $Q_{in} = 80W$) using the mathematical model of example 1;

Figures 17A and 17B are graphical representations of Functionality of R_{tot} and Functionality of Π_0 with three proposed independent dimensionless numbers respectively;

Figure 18 is a graphical representation of modelled thermal resistance of the heat pipe and predicted values using Eq. 44 and Eq. 43 of the mathematical model of example 1;

Figure 19A is a graphical representation of thermal resistance vs. three proposed dimensionless numbers for the mathematical model of example 1;

Figure 19B is a graphical representation of effect of molecular size and structure of working fluid on total thermal resistance of heat pipe;

Figure 20 is a flow diagram representation a method for conducting a simulation in relation to example 2;

Figure 21 is a schematic diagram of an example of an experimental setup for example 2;

Figure 22 is a schematic of an example heat pipe with axial swallow-tailed microgrooves (illustrations not to scale);

Figures 23A to 23C are graphical representations of a comparison of simulation results with experimental results of example 2;

Figure 24 is a graphical representation of Model data vs. experimental data for $T_{f,N}$ and T_i for example 2;

Figure 25 is a schematic diagram of an example of a modelled system;

Figure 26 is a graphical representation of typical Sydney weather data on the first day of January 2006;

Figure 27 is a graphical representation of the heat pipe condenser and evaporator thermal resistance over 24 hours using water as working fluid (HP_{10});

Figure 28 is a graphical representation of total thermal resistance ratio of different working fluids relative to water (HP_{10});

Figure 29 is a graphical representation of CHF vs. simulation time for water as working fluid (HP_{10});

Figure 30 is a graphical representation of CHF vs. simulation time for different working fluids Relative to water (HP_{10});

Figure 31 is a graphical representation of CHF vs. simulation time for different working fluids Relative to water (HP_{10});

Figure 32 is a graphical representation of CHF vs. simulation time for Water and Ammonia for the built-in heat pipes;

Figure 33 is a graphical representation of total thermal resistance ratio of nominated hypothetical working fluids Relative to water;

Figure 34 is a graphical representation of CHF of nominated hypothetical working fluids relative to water;

Figure 35 is a schematic diagram of an example modelled system for annual analysis;

Figure 36 is a graphical representation of a maximum transferred heat in each day during a year for water and Hyp_3 for the example modelled system of Figure 35;

Figure 37 is a graphical representation of an amount of lost energy due to lack of CHF for Water and Hyp_3 as working fluid for the example modelled system of Figure 35;

Figure 38 is a graphical representation of a trend of objective function using pattern search as the optimization method for example 3;

Figure 39 is a graphical representation of a trend of objective function using GA as the optimization method for example 3; and

Figure 40 is a graphical representation of a trend of objective function using pattern search and genetic algorithm as the optimization method for example 3.

Detailed Description

The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

In the context of this specification, the word "comprising" means "including principally but not necessarily solely" or "having" or "including", and not "consisting only of". Variations of the word "comprising", such as "comprise" and "comprises" have correspondingly varied meanings.

The present invention provides a method of determining, or identifying, the desirable thermophysical properties of a working fluid for a particular assembly that involves the transfer of thermal energy between a heat source and a heat sink.

In certain embodiments the present invention is particularly aimed at identifying the desirable thermophysical properties of a working fluid that undergoes a phase change

between liquid and vapour during the transfer of thermal energy in an assembly. The types of assemblies that are of particular relevance are those assemblies including one or more heat pipes and/or heat pumps. By determining the thermophysical properties which are most desirable in a working fluid for a particular assembly, then optimum working efficiencies can be obtained for the transfer of thermal energy in the assembly in question.

What is considered to be the desirable thermophysical properties may provide a number of results and within the context of the present invention depends upon the objective function that is defined with respect to the mathematical model of the assembly that is provided.

In certain embodiments the objective function determined in the method of the present invention may be selected from one or more of the following:

Economic objective functions:

$$obj = \frac{C_{HP} \times N_{HP}}{\max\left[0,(Q_D - N_{HP} \times \min\left[0,\left(\max(Q_{trans}) - CHF\right)^2\right)\right]^2}$$

$$obj = C_{elec.} \times (Q_D - Q_{trans}) + C_{elec.} Q_D \times \max\left[0,\left(\max(Q_{trans}) - CHF\right)\right]^2$$

Techno-economic objective functions:

$$obj = C_{elec.} \times (Q_D - Q_{trans}) + C_{elec.} Q_D \times \left(\max(Q_{trans}) - CHF\right)$$

Technical objective functions:

$$obj_{property} = \sum\left(\frac{property_{opt} - property_{mix}}{property_{opt}}\right)^2$$

"Property" may be a specific selection or all of the mentioned one or more thermophysical properties of the working fluid in both liquid and vapour phase.

$$obj_{property} = \sum\left(\frac{property_{opt} - property_{mix}}{property_{opt}}\right)$$

$$obj_{property,i} = \frac{property_{opt,i} - property_{mix,i}}{property_{opt,i}}_{i=1\,to\,N}$$

This includes several objective functions which may be suitable for multi-objective optimization, i is the number of targeted thermophysical properties

$$obj_{DA} = \sum\left(\frac{DA_{opt} - DA_{mix}}{DA_{opt}}\right)^2$$

"DA" is related to the dimensionless numbers and the figure of merit as hereindefined.

$$obj_{DA,i} = \frac{DA_{opt,i} - DA_{mix,i}}{DA_{opt,i}}_{i=1\,to\,N}$$

This includes several objective functions which may be suitable for multi-objective optimization, i is the number of targeted dimensionless numbers and figure of merit properties.

Dimensional Analysis

In certain embodiments, the mathematical model of the assembly depends upon greater than three and often greater than five thermophysical properties of the working fluid. In such embodiments, the mathematical model becomes substantially complex because it is highly nonlinear and multidimensional in nature. In the event the mathematical model consists of at least six relevant dimensions including the thermophysical properties of the working fluid including thermal conductivity, surface tension, latent heat, increasing viscosity, and liquid density the resulting set of differential-integral-algebraic system of equations which represents such a model requires extensive computational effort as well as an effective graphical representation to solve for any given criteria.

According to certain embodiments, there is therefore provided a method based on dimensional analysis to simplify the evaluation of each effective property on the mathematical model.

Based on this approach and using Π method the dimension of the domain of the problem is reduced from eight (including the six thermophysical properties above as well as working temperature and heat input) to four by developing four dimensionless numbers and characterizing the resulting 4-D problem.

For example, the first step for developing dimensionless numbers for a problem is to define a complete set of independent quantities. A set is complete if once the values of the members are specified, no other quantity can affect the value of the dependent variable. A set is independent if the value of each member can be adjusted arbitrarily without affecting the value of any other member. The affecting quantities of the problem are: $h_{fg}, Q_{in}, T, \rho_l, \sigma, k, \mu_l$ and the dependent quantity that we would like to calculate is R_{tot}.

The second step is to list the dimensions of the dependent variable and the independent variables. The dimensions of the independent and dependent quantities are shown in Table-b 1.

Table-b 1- dimensions of the independent and dependent quantities

Quantity	Dimension	Quantity	Dimension
h_{fg}	L^2t^{-2}	ρ_l	ML^{-3}
Q_{in}	ML^2t^{-3}	σ	Mt^{-2}
T	θ	k	$MLt^{-3}\theta^{-1}$
R_{tot}	$M^{-1}L^{-2}t^3\theta$	μ_l	$ML^{-1}t^{-1}$

The third step is to define the dimensionless forms of the remaining quantities which are $h_{fg}, Q_{in}, T, R_{tot}$. To do so, first the exponent of the following Eq. B- 1 to Eq. B- 4 should be calculated by solving the set of algebraic equations for each one of them.

$$h_{fg} = k^{e_{1,1}} \mu_l^{e_{1,2}} \sigma^{e_{1,3}} \rho_l^{e_{1,4}} \quad \textbf{Eq. B- 1}$$

$$Q_{in} = k^{e_{2,1}} \mu_l^{e_{2,2}} \sigma^{e_{2,3}} \rho_l^{e_{2,4}} \quad \textbf{Eq. B- 2}$$

$$T = k^{e_{1,1}} \mu_l^{e_{1,2}} \sigma^{e_{1,3}} \rho_l^{e_{1,4}} \quad \textbf{Eq. B- 3}$$

$$R_{tot} = k^{e_{1,1}} \mu_l^{e_{1,2}} \sigma^{e_{1,3}} \rho_l^{e_{1,4}} \quad \textbf{Eq. B- 4}$$

The solution for Eq. B- 1 is presented here as an example.

$$L^2 t^{-2} = \left(MLt^{-3}\theta^{-1}\right)^{e_{1,1}} \left(ML^{-1}t^{-1}\right)^{e_{1,2}} \left(Mt^{-2}\right)^{e_{1,3}} \left(ML^{-3}\right)^{e_{1,4}} \quad \textbf{Eq. B- 5}$$

The following system of equations is the results of the Eq. B- 5.

$$M: 0 = e_{1,1} + e_{1,2} + e_{1,3} + e_{1,4} \quad \textbf{Eq. B- 6}$$

$$L: \ 2 = e_{1,1} - e_{1,2} - 3e_{1,4}$$

$$t: -2 = -3e_{1,1} - e_{1,2} - 2e_{1,3}$$

$$\theta: \ 0 = -e_{1,1}$$

Solution of the above system is:

$$e_{1,1} = 0 \quad \textbf{Eq. B- 7}$$

$$e_{1,2} = -2$$

$$e_{1,3} = 2$$

$$e_{1,4} = 0$$

Then the corresponding dimensionless number is obtained as follows:

$$\Pi_1 = \frac{k^{e_{1,1}} \mu_l^{e_{1,2}} \sigma^{e_{1,3}} \rho_l^{e_{1,4}}}{h_{fg}} \Rightarrow \Pi_1 = \frac{\sigma^2}{h_{fg} \mu_l^2} \quad \textbf{Eq. B- 8}$$

In the same way other dimensionless numbers can calculated. Π_0 is called dependent dimensionless number because it is the only number that contains the dependant variable R_{tot}. Therefore, Π_0 is the dependant variable of the dimensionless problem and other numbers are independent variables.

At the end, the dependent variable can be shown in form of a function of independent variables and the form of the function is determined by experimental data. In this example, the results of the developed model are treated as experimental data.

$$\Pi_0 = f(\Pi_1, \Pi_2, \Pi_3) \qquad \textbf{Eq. B- 9}$$

The developed dimensionless numbers are presented in Eq. 1 to Eq. 4.

$$\Pi_0 = \frac{\sigma \rho_l}{k \mu_l^2 R_{tot}} \qquad \textbf{Eq. 1}$$

$$\Pi_1 = \frac{\sigma^2}{\mu_l^2 h_{fg}} \qquad \textbf{Eq. 2}$$

$$\Pi_2 = \frac{\sigma \mu_l}{\rho_l Q_{in}} \qquad \textbf{Eq. 3}$$

$$\Pi_3 = \frac{\sigma^2}{k \mu_l T} \qquad \textbf{Eq. 4}$$

Π_0 is the dependant dimensionless number and is intended to imitate the behaviour of thermal resistance. Π_1, Π_2 and Π_3 are independent dimensionless numbers (new variables of the 4-D problem) and solely contain working fluid and working condition parameters.

Π_1, Π_2 and Π_3 are perfect representatives of the dimensionally reduced system. However, Π_0, as a new dimensionless number, carries a physical meaning, it is proportional to the ratio of dimensionless temperature gradient in the heat pipe (modified Nusselt number, Nu as in Eq. 6) to the ratio of inertia to surface tension forces (Weber number, We as in Eq. 7) multiplied by the square of ratio of inertia to viscous forces (Reynolds number, Re as in Eq. 8). The mathematical representation of Π_0 is show in Eq. 5 below.

$$\Pi_0 = \gamma \frac{\mathrm{Nu}\,\mathrm{Re}^2}{\mathrm{We}} \qquad \textbf{Eq. 5}$$

$$\mathrm{Nu} = \frac{\delta_{ave} h_{eff}}{k} = \frac{\delta_{ave}}{k R_{tot} A_{eff}} \qquad \textbf{Eq. 6}$$

$$\mathrm{We} = \frac{\rho_l u_l^{\,2} D_{h,l}}{\sigma} \qquad \text{Eq. 7}$$

$$\mathrm{Re} = \frac{\rho_l u_l D_{h,l}}{\mu_l} \qquad \text{Eq. 8}$$

$$\gamma = \frac{A_{eff}}{\delta_{ave} D_{h,l}} \qquad \text{Eq. 9}$$

$$A_{eff} = N_g \left(\frac{\omega_1 + \omega_2}{2}\right)(L_e + L_c) \qquad \text{Eq. 10}$$

In the above equations, Nu has been defined based on the effective heat transfer coefficient of the heat pipe, h_{eff}, which can also be shown as the total thermal resistance of heat pipe in the heat transfer direction, $\frac{1}{R_{tot} A_{eff}}$. This is a very common way of correlating heat transfer coefficients and thermal resistance in a heat transfer tools. γ is No spe Re and We can be used based on their common definition (as shown in Eq. 7 and Eq. 8).

It is worth to mention that since the proposed set of dimensionless numbers are completely independent of the structure, type, geometry of an assembly, and the working fluid, this method can be used for any assembly involving the transfer of thermal energy between a heat source and a heat sink with arbitrary dimension and working fluid.

A particular embodiment of the present invention can be realised using a processing system, an example of which is shown in Fig. 1. In particular, the processing system 100 generally includes at least one processor 102, or processing unit or plurality of processors, memory 104, at least one input device 106 and at least one output device 108, coupled together via a bus or group of buses 110. In certain embodiments, input device 106 and output device 108 could be the same device. An interface 112 can also be provided for coupling the processing system 100 to one or more peripheral devices, for example interface 112 could be a PCI card or PC card. At least one storage device 114 which houses at least one database 116 can also be provided. The memory 104 can be any form of memory device, for example, volatile or non-volatile memory, solid state storage devices, magnetic devices, etc. The processor 102 could include more than one distinct

processing device, for example to handle different functions within the processing system 100.

Input device 106 receives input data 118 and can include, for example, a keyboard, a pointer device such as a pen-like device or a mouse, audio receiving device for voice controlled activation such as a microphone, data receiver or antenna such as a modem or wireless data adaptor, data acquisition card, etc. Input data 118 could come from different sources, for example keyboard instructions in conjunction with data received via a network. Output device 108 produces or generates output data 120 and can include, for example, a display device or monitor in which case output data 120 is visual, a printer in which case output data 120 is printed, a port for example a USB port, a peripheral component adaptor, a data transmitter or antenna such as a modem or wireless network adaptor, etc. Output data 120 could be distinct and derived from different output devices, for example a visual display on a monitor in conjunction with data transmitted to a network. A user could view data output, or an interpretation of the data output, on, for example, a monitor or using a printer. The storage device 114 can be any form of data or information storage means, for example, volatile or non-volatile memory, solid state storage devices, magnetic devices, etc.

In use, the processing system 100 is adapted to allow data or information to be stored in and/or retrieved from, via wired or wireless communication means, the at least one database 116. The interface 112 may allow wired and/or wireless communication between the processing unit 102 and peripheral components that may serve a specialised purpose. The processor 102 receives instructions as input data 118 via input device 106 and can display processed results or other output to a user by utilising output device 108. More than one input device 106 and/or output device 108 can be provided. It should be appreciated that the processing system 100 may be any form of terminal, server, specialised hardware, or the like.

The processing system 100 may be a part of a networked communications system 200, as shown in Fig. 2. Processing system 100 could connect to network 202, for example the

Internet or a WAN. Input data 118 and output data 120 could be communicated to other devices via network 202. Other terminals, for example, thin client 204, further processing systems 206 and 208, notebook computer 210, mainframe computer 212, PDA 214, pen-based computer 216, server 218, etc., can be connected to network 202. A large variety of other types of terminals or configurations could be utilised. The transfer of information and/or data over network 202 can be achieved using wired communications means 220 or wireless communications means 222. Server 218 can facilitate the transfer of data between network 202 and one or more databases 224. Server 218 and one or more databases 224 provide an example of an information source.

Other networks may communicate with network 202. For example, telecommunications network 230 could facilitate the transfer of data between network 202 and mobile or cellular telephone 232 or a PDA-type device 234, by utilising wireless communication means 236 and receiving/transmitting station 238. Satellite communications network 240 could communicate with satellite signal receiver 242 which receives data signals from satellite 244 which in turn is in remote communication with satellite signal transmitter 246. Terminals, for example further processing system 248, notebook computer 250 or satellite telephone 252, can thereby communicate with network 202. A local network 260, which for example may be a private network, LAN, etc., may also be connected to network 202. For example, network 202 could be connected with ethernet 262 which connects terminals 264, server 266 which controls the transfer of data to and/or from database 268, and printer 270. Various other types of networks could be utilised.

The processing system 100 is adapted to communicate with other terminals, for example further processing systems 206, 208, by sending and receiving data, 118, 120, to and from the network 202, thereby facilitating possible communication with other components of the networked communications system 200.

Thus, for example, the networks 202, 230, 240 may form part of, or be connected to, the Internet, in which case, the terminals 206, 212, 218, for example, may be web servers, Internet terminals or the like. The networks 202, 230, 240, 260 may be or form part of

other communication networks, such as LAN, WAN, ethernet, token ring, FDDI ring, star, etc., networks, or mobile telephone networks, such as GSM, CDMA or 3G, etc., networks, and may be wholly or partially wired, including for example optical fibre, or wireless networks, depending on a particular implementation.

The processing system 100 may be configured by a computer readable medium including executable instructions in the form of a computer program. Upon execution of the computer program, the processing system 100 is configured to perform the method described above. The compute readable medium may be memory such as a hard drive of the processing system 100, or portable memory (CD, DVD, etc.) or the like.

Referring to Figure 3 there is shown a method of determining a working fluid for an assembly using a processing system 100 as described in relation to Figures 1 and 2.

At step 310, an executable software application is launched by the processing system 100 for determining the working fluid of an assembly. The application can be stored in memory of the processing system 100 or alternatively can be stored remotely (i.e. cloud computing).

In particular, at step 320 the method includes a user operating the processing system 100 selecting a mathematical model for the assembly using one or more input devices of the processing system 100. In particular, the mathematical model may be selected from a library of mathematical models which are stored in memory of the processing system 100 or are stored in a remote storage device which the processing system 100 can access using one or more communication networks. The mathematical models are stored as mathematical model data in memory indicative of various equations for determining the working fluid for the assembly.

At step 330, the method includes the processing system 100 optionally obtaining temporal heat source data. In particular, the temporal heat source data may be input to the application by the user. For example, the temporal heat source data may be stored in a file

in memory of the processing system 100 or remotely in a remote storage device, wherein the user can indicate to the application the location of the temporal heat source file. Alternatively, the application may automatically obtain temporal heat source data from local memory or from a remote storage device. In particular applications such as solar hot water heaters, (TMY) typical metrological year data may be obtained by the application for a specific geographical location. In this example, the user may input via the input device a geographical location, wherein the temporal heat source data is obtained by the processing system 100 which corresponds to the geographical location input by the user. It will be appreciated that for particular applications, temporal heat source data is not required.

At step 340, the method includes the processing system 100 optionally obtaining, from the user, performance criteria for the assembly from the user. In particular, the user may input via the input device of the processing system 100 performance criteria values such as a required critical heat flux and/or thermal resistance of the assembly. However, it will be appreciated that the mathematical model selected may include predefined performance criteria and thus the user is not required to define these values for the method.

At step 350, the method optionally includes the user providing input indicative of a first and optionally a second objective function for use in determining the working fluid for the assembly. In particular, the application has access to objective function data indicative of a plurality of first and/or second objective functions, wherein the application present the user with an indication of plurality of first and/or second objective functions which the user can select from to perform the optimisation process. In response to the selection from the user via the input device of the processing system 100, the processing system 100 records data in memory indicative of the selected first and/or second optimisation functions used for determining the working fluid for the assembly. It will be appreciated that this step can be optional as particular mathematical models may have predefined objective functions which do not require user selection.

At step 360, the method includes the processing system 100, under control of the application, performing a first optimisation process to determine thermophysical properties

of an hypothetical fluid for the assembly represented by the mathematical model. In particular, the mathematical model includes a modelled fluid having a plurality of thermophysical properties which can be manipulated by the processing system 100 using an optimisation algorithm. For each iteration of the first optimisation process, an output value of the first objective function is calculated in relation to the mathematical model which is dependent upon the plurality of thermophysical properties of the modelled fluid.

As the first optimisation process is executed by the processing system 100 under the control of the application, the processing system 100 modifies one or more of the thermophysical properties of the modelled working fluid in each optimisation iteration in order to meet a goal of the first objective function. For example, if the first objective function is a techno-economic function, the processing system 100 modifies one or more of the thermophysical properties of the modelled working fluid in the mathematical model in order to seek a minimised economic cost for operating the assembly based on technical characteristics. Thus, as the first optimisation process continues to operate, an optimised version of the modelled working fluid is eventually identified (generally a global maxima or minima) by the processing system 100 under control of the application (i.e. the thermophysical properties that define the optimised version of the modelled working fluid) which satisfies the goal of the first objective function. This optimised version of the modelled working fluid is thereby the hypothetical fluid which is optimal for use for the assembly.

The application can utilise various types of optimisation processes to conduct the first optimisation process. In one form, the first optimisation process can utilise genetic algorithm (GA) or pattern search (PS) to modify the thermophysical properties of the modelled working fluid to identify the thermophysical properties of the optimised hypothetical fluid for the mathematical model of the assembly.

The processing system 100, under control of the application, modifies the one or more thermophysical properties of the modelled working fluid within a range of thermophysical property values. In one form, the processing system 100 has stored in memory or in a

remote storage device, thermophysical property range data based upon a known fluids list and their known thermophysical properties.

It will be appreciated that it is unlikely that the hypothetical fluid does not exist in nature. Thus, the method then continues to step 370 to determine, based on the determined hypothetical fluid, a real fluid or fluid mixture which possesses thermophysical properties as close as possible to the thermophysical properties of the optimised hypothetical fluid.

In one form, the processing system 100 can determine a discrepancy between the thermophysical properties of each known fluid in the known fluid list against the thermophysical properties of the determined optimised hypothetical fluid, wherein the real fluid which has the lowest discrepancy is identified as the working fluid for the assembly. The results of this comparison can be output to the user via the output device of the processing system 100 at step 380. The assembly can then be manufactured by a plant to include the identified working fluid which is the most optimal fluid from the known fluid list.

In an alternate form, the processing system 100 can perform a second optimisation process at step 370 in relation to a second output of the second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture.

Specifically, the processing system 100 iteratively defines a fluid mixture comprising of a plurality of fluids from the known fluid list, wherein the fluid mixture is manipulated according to the results of the second objective function in accordance with the second optimisation process. In particular, the processing system 100, under control of the application, iteratively manipulates at least one of a number of fluids selected from the known fluid, a selection of fluids from the known fluid list, and a proportion of each selected fluid. By manipulating the selection of fluids, the number of fluids and the proportion of each selected fluid, the processing system 100 inherently modifies the thermophysical properties of the fluid mixture. Thus, during each modified iteration, the

processing system 100 determines the thermophysical properties of the fluid mixture based upon the modifications to the selection of fluids, the number of fluids and the proportion of each selected fluid. The determined thermophysical properties of the fluid mixture are then used by the second objective function to determine modifications to fluid mixture to reach a global maxima or minima.

In one particular form, a goal of the second objective function is to minimise the discrepancy between the thermophysical properties of the fluid mixture and the hypothetical fluid. Thus, each iteration of the second optimisation process which is performed by the processing system 100 attempts to define a fluid mixture which possesses thermophysical properties which satisfy this goal of the second objective function.

Upon detection of a global maxima or minima by the processing system 100, under control of the application, the processing system 100 outputs via the output device details the fluid mixture such as the selection of fluids and the respective proportions at step 380. The assembly can thus be manufactured by a plant using the fluid mixture according to the output generated by the processing system 100.

It will be appreciated that due to the first and second optimisation processes that the processing system is applying, it is possible for the processing system to determine multiple real working fluids optimised for the assembly through multiple operations of the optimisation process using different starting points. Thus, the method 300 can be performed multiple times to identify a plurality of real working fluids. Experiments can then be performed using the multiple working fluids and the assembly to identify a single working fluid which is optimal for the assembly. It will be appreciated that in this scenario, the method is used for filtering the high number of combinations of fluid mixtures such that only a very small subset need to be tested. This therefore reduces substantial time as well as experimental costs.

In another arrangement, the processing system can perform the first and second optimisation processes a plurality of iterations such that a plurality of real fluids which

make up the determined plurality of potential working fluids is identified. The processing system then performs a third optimisation process, under control of the application, to identify a working fluid. The third optimisation process is performed using the same technique as the second optimisation process. However, for the third optimisation process, the known fluid list data is modified by the processing system to include only the known fluids which form the fluid mixtures determined after the multiple applications of the second optimisation process. By reducing the selection of known fluids to be considered by the processing system for the third optimisation process to those which have been identified as being components of for the potential working fluids, a more comprehensive optimisation process may be performed in the third optimisation process to determine an optimised fluid mixture for use as the working fluid for the assembly.

The present invention will now be further described in connection with the following example embodiments of various aspects of the present invention:

EXAMPLE 1

As an example of a mathematical model of an assembly involving the transfer of thermal energy between a heat source and a heat sink with that is dependent upon one or more thermophysical properties of a working fluid, the following is a description of a mathematical model that includes the effect of hydrodynamics on thermal resistance of the heat pipe. A schematic diagram of the example heat pipe with axial swallow-tailed microgrooves is shown in Figure 4.

Heat transfer limitations

The hydrodynamics modelling of the heat pipe is governed by a set of equations related to pressure drop in liquid and vapour phase of working fluid. The self circulation of the working fluid inside the heat pipe is driven by the capillary pressure generated by micro grooves. Therefore, for any location along the heat pipe, the capillary pressure is equal to pressure difference between liquid and vapour phase. The Laplace-Young equation is used to calculate this pressure difference (Eq. 11).

$$P_c = P_v - P_l = \sigma\left(\frac{1}{r_{cr}} + \frac{1}{r_{ca}}\right) \quad \textbf{Eq. 11}$$

Since r_{ca} is much larger than r_{cr}, the axial capillary radius can be neglected. The differential form of Eq. 11 is:

$$\frac{dP_v}{dz} - \frac{dP_l}{dz} = -\frac{\sigma}{r_{cr}^2(z)}\frac{dr_{cr}(z)}{dz} \quad \textbf{Eq. 12}$$

Vapour and liquid pressure drop along heat pipe can be calculated from Eq. 13 and Eq. 14:

$$\frac{dP_v}{dz} = -\frac{2\mu_v C f_v \mathrm{Re}_v}{D^2_{v,h}}\frac{\dot{m}_v(z)}{A_{v,h}\rho_v} \quad \textbf{Eq. 13}$$

$$\frac{dP_l}{dz} = -\frac{2\mu_l f_l \mathrm{Re}_l}{D^2_{l,h}}\frac{\dot{m}_l(z)}{NA_{l,h}\rho_l} \quad \textbf{Eq. 14}$$

The gravitational pressure drop in liquid phase is neglected since the heat pipe is horizontal in this study. The effect of filling ratio and accumulation of the working fluid at the end cap of the condenser section are also neglected. The evaporator and condenser section are under uniform heat flux condition. Therefore, the mass flow rate can be calculated from Eq. 15.

$$\dot{m}_l(z) = -\dot{m}_v(z) = -\frac{Q(z)}{h_{fg}} \quad \textbf{Eq. 15}$$

The axial heat load distribution is:

$$Q(z) = \begin{cases} \dfrac{z}{L_e}Q_{in} & 0 \le z \le l_e \\ Q_{in} & l_e < z < L_e + L_a \\ \dfrac{L_e + L_a + L_c - z}{L_c}Q_{in} & L_e + L_a \le z \le L_e + L_a + L_c \end{cases} \quad \textbf{Eq. 16}$$

The value of meniscus radius at the end cap of the condenser can be obtained from geometry and is equal to the vapour channel radius. This is the boundary condition at $z = L_e + L_a + L_c$. The Poiseuille numbers for liquid and vapour phase are calculated using Eq. 17 to Eq. 20.

$$\mathrm{Re}_v = \frac{4\dot{m}_v}{\pi D_v \mu_v} \qquad \textbf{Eq. 1'}$$

$$\mathrm{Ma}_v = \frac{\dot{m}_v}{\rho_v A_v \sqrt{\gamma_v R T_v}} \qquad \textbf{Eq. 1}$$

$$C \times f_v \mathrm{Re}_v = \begin{cases} 16 & \mathrm{Re}_v < 2300 \,\&\, Ma_v < 0.2 \\ \dfrac{16}{\sqrt{1 + \dfrac{\gamma_v - 1}{2} \mathrm{Ma}_v^{\,2}}} & \mathrm{Re}_v < 2300 \,\&\, Ma_v > 0.2 \\ 0.038 \left(\dfrac{D_v Q_{in}}{A_v \mu_v h_{fg}} \right)^{3/4} & \mathrm{Re}_v > 2300 \,\&\, Ma_v < 0.2 \\ 0.608 \left(\dfrac{D_v Q_{in}}{A_v \mu_v h_{fg}} \right)^{3/4} \dfrac{1}{\sqrt{1 + \dfrac{\gamma_v - 1}{2} \mathrm{Ma}_v^{\,2}}} & \mathrm{Re}_v > 2300 \,\&\, Ma_v > 0.2 \end{cases} \qquad \textbf{Eq. 1}$$

$$f_l \mathrm{Re}_l = \begin{cases} 14.11\alpha^{0.06009} \times e^{-0.5\left(\frac{Log\left(\frac{A_s}{22.22\alpha^{-0.3366}}\right)}{2.083\alpha^{0.0372}} \right)^2} & \dfrac{h_g}{\omega_2} > 1.5 \\ 5.753\alpha^{0.1841} + \left(173.9 - 5.3737\alpha + 0.0621\alpha^2 - 0.0002\alpha^3\right) & \dfrac{h_g}{\omega_2} < 1.5 \\ \times e^{\left(-8.899 + 0.1511\alpha - 2.196E\text{-}3\alpha^2 + 7.866E\text{-}6\alpha^3\right) A_s} + (2.172 + 0.0011\alpha) A_s & \end{cases} \qquad \textbf{Eq. 2}$$

Therefore, the hydrodynamics of the working fluid in the heat pipe is determined by substituting all the above equations in Eq. 12 and solving the resulting equation using fifth order Runge-Kutta method. While the micro-grooved axially swallow-tailed heat pipe worked under steady state condition and reaches the CHF (Critical Heat Flux), the meniscus is anchored at the opening edge of the groove. Therefore, the capillary radius can be expressed as Eq. 21.

$$r_{cr,\min} = \frac{\omega_1 / 2}{\cos(\bar{\alpha})} \qquad \textbf{Eq. 21}$$

$$\bar{\alpha} = \frac{\int_0^{L_e + L_a + L_c} \alpha \, dz}{L_e + L_a + L_c} \qquad \textbf{Eq. 22}$$

Since the contact angle is not constant along the heat pipe the average value is used based on Eq. 22. Contact angle of the working fluid is going to be calculated using the model since it is highly dependent on meniscus radius (refer to Appendix A). The procedure for calculating CHF is based on trial and error as described in the following steps:

Step 1: Guess a relatively small value for Q_{in}

Step 2: Run the model and calculate $\min(r_{cr})$

Step 3: Compare $\min(r_{cr})$ with $r_{cr,min}$

Step 4: If $\min(r_{cr}) > r_{cr,min}$ increase Q_{in} otherwise decrease Q_{in}

Step 5: Repeat steps 2-4 until reaching convergence at desired accuracy.

Thermal resistance estimation

The total thermal resistance is another important factor to determine the performance of a heat pipe. The focus of this example is on improvement of this factor rather than CHF (Critical Heat Flux). The heat flow paths and thermal resistances at the evaporator section and the condenser section for the heat pipe under study are shown in Figure 5. Two main paths for heat transfer in axially grooved heat pipes are recognised. The first one is heat transfer through metal container and then through liquid-saturated wick (macro region). The second path is through metal container, metal fins and then through a very thin liquid film region (micro region). The latter is the most important path in evaporator section.

At the condenser, the first path is the same but the second path is through condensation of the vapour on the fins and forming a micro thin film of liquid and then through fin and the metal container wall. For the purposes of this example, it is assumed that 80% of the total heat input is transferred through micro thin film in condenser section. The mentioned heat transfer paths are also shown in Figure 5.

Thermal resistance of the condenser and evaporator is formulated using thermal resistance circuit concept. The results are presented in Eq. 23 to Eq. 37.

$$R_e = \frac{(R_1 + R_2 + R_3)(R_4 + R_5)}{L_e N_g (R_1 + R_2 + R_3 + 2(R_4 + R_5))} \quad \text{Eq. 23}$$

$$R_c = \frac{(R_6 + R_7 + R_8)(R_9 + R_{10})}{L_c N_g (R_6 + R_7 + R_8 + 2(R_9 + R_{10}))} \quad \text{Eq. 24}$$

$$R_a = \frac{T_{v,e} T_{v,c} R \log(\frac{P_v|_{z=0}}{P_v|_{z=L}})}{h_{fg} Q_{in}} \quad \text{Eq. 25}$$

$$R_{tot} = R_e + R_a + R_c \quad \text{Eq. 26}$$

$$\Delta T_{wall(e|c)} = R_{tot} Q_{in} \quad \text{Eq. 27}$$

R_a is the thermal resistance due to vapour flow in adiabatic section. The values of R_a are determined on an iteration basis. However, R_a is very small relative to other thermal resistances and can be neglected.

$$R_1 = \frac{t_{wall,e}}{k_{pipe} \omega_{fin}} \quad \text{Eq. 28}$$

$$R_6 = \frac{\bar{\delta}_{film,c}}{k_f \omega_{fin}} \quad \text{Eq. 29}$$

$$R_2 = \frac{\bar{\delta}_e}{k_{pipe} \omega_{fin}} \quad \text{Eq. 30}$$

$$R_7 = \frac{t_{fin}}{k_{pipe} \omega_{fin}} \quad \text{Eq. 31}$$

$$R_3 = \frac{0.185 \omega_{fin}}{k_f (h_g - \bar{\delta}_e)} \quad \text{Eq. 32}$$

$$R_8 = \frac{t_{wall,c}}{k_{pipe} \omega_{fin}} \quad \text{Eq. 33}$$

$$R_4 = \frac{t_{wall,e}}{k_{pipe} \omega_o} \quad \text{Eq. 34}$$

$$R_9 = \frac{\bar{\delta}_c}{k_f \omega_1} \quad \text{Eq. 35}$$

$$R_5 = \frac{\bar{\delta}_e}{k_f \omega_2} \quad \text{Eq. 36}$$

$$R_{10} = \frac{t_{wall,c}}{k_{pipe} \omega_2} \quad \text{Eq. 37}$$

The thickness of micro-thin film of liquid in condenser is calculated using Eq. 38. The mean value of meniscus radius is calculated using numerical integration within appropriate range of z (Eq. 39). Mean value for all other continues parameters like $\bar{\delta}_{y,c}$ and $\bar{\delta}_{y,e}$ are calculated using similar concept.

$$\bar{\delta}_{film,c} = \left(\frac{6\mu_l \omega_{fin} Q_{mic} \bar{r}_{cr,c}}{L_c N_g \sigma \rho_l h_{fg}} \right)^{1/3} \qquad \text{Eq. 38}$$

$$\bar{r}_{cr,c} = \frac{\int_{l_e+l_a}^{l_e+l_a+L_c} r_{cr} dz}{L_c} \qquad \text{Eq. 39}$$

Model validation

To provide some validation for the proposed mathematical model of this example, the model is run for an Aluminium-Ammonia micro-grooved heat pipe and the results are presented in Figures 6 to 8. In particular, results shown in Figures 6 to 8 are compared to the model developed by Chen et al (*Thermal Characteristics of Heat Pipe with Axially Swallow-tailed Microgrooves.* Chinese Journal of Chemical Engineering, 2010. 18(2): p. 185-193.) Specifically, Figure 6 is a graphical representation of a comparison of calculated pressure distribution ($T = 27^{\circ}C$ and $Q_{in} = 100W$ $Q_{in} = 212.3W$), Figure 7 is graphical representation of a comparison of calculated meniscus radius ($T = 27^{\circ}C$ and $Q_{in} = 212.3W$) and Figure 8 is a graphical representation of a comparison of calculated critical heat flux vs. temperature.

The details of geometry of the heat pipe are presented in Table 1. As shown in Figure 6 and Figure 7, the results show good agreement with the model developed by Chen et al. However, there is a very small difference in the calculated meniscus radius. The main reason is a fairly simple model is used for calculation of Poiseuille number of vapour and liquid phase in this study. The other reason is the contact angle is not constant and is calculated along the heat pipe length.

Table 1-The details of the heat pipe geometry and working condition.

Casing	Fluid	T/C	D_o/mm	D_v/mm	L_e/m	L_a/m	L_c/m	N_g	h_g/mm	$\frac{h_g}{\omega_2}$
Aluminium	Ammonia	27	14.96	10	0.7	0.65	0.65	22	1.28	1.42

In this example, the validated model is applied on a heat pipe which may be suitable for a variety of applications including solar applications and more specifically suitable for solar water heaters. The details of geometry of the heat pipe are presented in Table 2.

Different working fluids (namely Water, Methanol, Acetone, Pentane, and Ammonia) are tested to observe the effect of changing the working fluid on meniscus radius and pressure distribution along the heat pipe. In this example, deionised Water is considered as the reference fluid due to its relative lower cost and availability. Therefore, all the comparisons are made relative to Water. The thermophysical properties of the tested working fluids at working temperature are included in Table 3.

Table 2- The details of the heat pipe geometry and working condition in this study.

Casing	T/C	D_o/mm	D_i/mm	L_e/m	L_a/m	L_c/m	N_g	h_g/mm	$\frac{h_g}{\omega_2}$	$2\upsilon/°$
Copper	50	14	12	1.7	0.1	0.2	60	1.28	4.07	75.8

Table 3- Thermophysical properties of the working fluids ($T = 50°C$).

	h_{fg}	ρ_l	ρ_v	k	μ_l	μ_v	P_{sat}	σ	*Merit*
Water	2.38E6	987.9	0.082	0.638	5.46E-4	1.08E-5	1.23E4	0.0679	2.92E11
Ammonia	1.07E6	562.9	15.64	0.264	1.85E-4	1.22E-5	2.25E6	0.0163	5.31E10
Methanol	1.12 E6	764.1	0.77	0.202	3.99e-4	1.04 E-5	5.5E4	0.0201	4.31E10
Acetone	5.27E5	756.1	1.600	0.172	2.47E-4	8.79E-6	8.53E4	0.0199	3.21E10
Pentane	3.49E5	596.2	5.315	0.130	1.86E-4	6.60E-6	1.86E5	0.0127	1.42E10

The calculated meniscus radius and pressure distribution along the heat pipe using the developed model are presented in Figure 9 and Figure 10. In particular Figure 9 shows graphically represents pressure distribution of different working fluids along the heat pipe ($T = 60°C$ and $Q_{in} = 50W$), and Figure 10 graphically represents meniscus radius distribution of different working fluids along the heat pipe ($T = 60°C$ and $Q_{in} = 50W$). As

can be seen, the change of the working fluid and subsequently the change in thermophysical properties highly affect the hydrodynamics of the working fluid within the heat pipe. The pressure drop along the heat pipe for water is the minimum and for Pentane is the maximum. Also it is shown in Figure 9 that the pressure drop for vapour phase is relatively small in comparison with pressure drop of liquid phase for different fluids. However, the difference is smaller for water. A pressure drop index (PDI) is suggested here to make this comparison simpler and independent of the used model (Eq. 40 and Eq. 41). The variation of the PDIs with temperature for the mentioned working fluids are shown in Figure 11. As shown in Figure 11, the effect of working temperature on relative vapour and liquid phases pressure drop is also easily noticeable using these indices. Again, in the tested working temperature (which is 50C) comparing the pressure drop results of the developed model with PDIs of the corresponding fluids validates the accuracy of the numerical solution of the model.

$$PDI_v = \frac{2 \times \mu_v}{\rho_v \times h_{fg}} \qquad \textbf{Eq. 40}$$

$$PDI_l = \frac{2 \times \mu_l}{\rho_l \times h_{fg}} \qquad \textbf{Eq. 41}$$

Effect of working fluid on thermal resistance

Using the developed model, the total thermal resistance of the heat pipe using different working fluids at different heat inputs are estimated. The transferable heat subject to different temperature differences between evaporator and condenser section of the heat pipe is shown in Figure 12. The thermal resistance versus imposed heat (heat input) is shown in Figure 13. As it is shown in Figure 13, as heat input increases, the thermal resistance of the heat pipe decreases and reaches a minimum. The length of each curve in Figure 12 and Figure 13 is a representative of the maximum capillary heat capacity (capillary limit) of the heat pipe which is calculated based on the procedure described. It is also observed that this limitation is proportional with the figure of merit of the working fluids as defined in Eq. 42. The effect of working temperature on CHF is shown in Figure 14 for comparison. Figure 15 shows the variation of figure of merit with temperature

which is useful for further investigation of the effect of working temperature on relative maximum capillary heat transfer capacity of heat pipes.

$$Figure\ of\ Merit = \frac{\rho_l \sigma h_{fg}}{\mu_l} \qquad \text{Eq. 42}$$

1-D sensitivity analysis

This example demonstrates the relationship between the effects of each thermophysical property of the working fluid on thermal resistance of a micro-grooved heat pipe through a comprehensive analysis on working fluid properties. Figure 13 shows that the thermal resistance of the heat pipe is highly influenced by hydrodynamics of the working fluid. Figure 13 shows that at higher heat inputs the difference between thermal resistance of the same heat pipe filled with different working fluids is smaller while this difference is much higher is lower heat inputs. In addition, as can be seen for Pentane and Acetone for instance, the ranking of working fluids based on thermal resistance may change as heat input changes.

Consider Pentane and Acetone as another example. At lower heat fluxes the thermal resistance of a heat pipe filled by Ammonia is significantly smaller than a heat pipe filled with Pentane. While at higher heat fluxes, which is quiet close to the capillary limit of Pentane, the thermal resistance of two heat pipes working with ammonia and Pentane is the same. This means that the rate of change in thermal resistance of a heat pipe filled with different working fluids is a very important factor that is critical in the analysis of thermal performance of a heat pipe.

To make the effect of thermophysical properties on thermal resistance more evident, the following sensitivity analysis on thermophysical properties of water as the reference working fluid is carried out and presented in Figure 16 (1-D sensitivity analysis for viscosity, surface tension, thermal conductivity, latent heat, and liquid density of water ($T = 50^{\circ}C$ and $Q_{in} = 80W$)). To produce this figure, the subjective thermophysical property

of water (namely Surface Tension, Latent heat, Liquid Density, Viscosity, and thermal conductivity) are changed from -50% to +50% of the original value in the working temperature while keeping other properties constant at original values. Therefore, Figure 16 serves only to show the magnitude and the trend of effect of each thermophysical property on the thermal resistance of the heat pipe. It can be seen that the effect of change in thermal conductivity of the working fluid is dominant. In addition, increasing viscosity of the working fluid is in favour of thermal resistance reduction while decreasing of latent heat, liquid density and surface tension are positive contributors to thermal resistance decrease.

Applicability of new dimensionless numbers

In order to demonstrate the applicability of the developed dimensionless numbers the 5-D simultaneous sensitivity analysis for Surface Tension, Latent Heat, Liquid Density, Viscosity, and Thermal Conductivity at a constant temperature and heat input is carried out. To do so, a set of unique values for each property is determined. Range of sensitivity analysis is -20% to +20% for each property on a 10% step size. The procedure of data generation can be described in following paragraph.

Using density as an example while other parameters are kept constant, density varies from 0.8 of the original value to 1.2 of original value. Then another property changes and again density changes in the mentioned range. In that way, a 5-D matrix for each property is produced. Other 5-D matrices are produced for other properties in the same way and simultaneously. Therefore, n^{th} member of each 5-D matrix corresponds to n^{th} member of the 5-D matrix for other properties. In this way, we have 5^5 members for each matrix which is equivalent to 5^5 unique set of data, and the model is run for each member and corresponding values of thermal resistance (which is the output of the developed model) produce the sixth 5-D matrix of data. Then these matrices are used to calculate corresponding dimensionless numbers.

The results are presented as 4-D graphs by putting the fourth dimension, which is the dependent variable (Π_0 or R_{tot}), in colormap in Figure 17A (Functionality of R_{tot}) and

Figure 17B (Functionality of Π_0 with three proposed independent dimensionless numbers). As can be seen in Figures 17A and 17B, the dependent dimensionless number and thermal resistance show complete functionality of other dimensionless numbers.

Applicability of dimensionless numbers

To put this in mathematical language, the integrity of the dependent variable (R_{tot}) with independent variables is investigated using a nonlinear multivariate regression method. Two forms of functions (presented in Eq. 44 and Eq. 43) are used to fit the calculated data using the Levenberg-Marquardt algorithm. The results of statistic tests are included in Table 4 and Figure 18.

$$R_{tot} = b_1 \Pi_1^{a_1} \Pi_2^{a_2} \Pi_3^{a_3} \quad \textbf{Eq. 43}$$

$$R_{tot} = b_1 \Pi_1^{a_1} + b_2 \Pi_2^{a_2} + b_3 \Pi_3^{a_3} \quad \textbf{Eq. 44}$$

Table 4- Results of nonlinear multivariate regression for water ($T = 50°C$ and $Q_{in} = 80W$)

		a_1	a_2	a_3	b_1	b_2	b_3	*RMSE*
Eq. 43	Value	-0.46	-0.37	0.89	1.03e-5	-	-	1.12e-4
	Err (%)	0.21	0.27	0.14	2.18	-	-	
Eq. 44	Value	0.19	-0.05	-0.20	-0.10	0.04	-0.04	5.95e-4
	Err (%)	16.13	5.58	11.76	1.28	11.05	18.91	

The residuals of two considered functions along with the predicted values for thermal resistance using Eq. 44 and Eq. 45 are shown in Figure 18. Very low RMSE and very low residuals prove a very good compatibility between the results of the model and the outputs of the fitted function. This shows the proposed set of dimensionless numbers is sufficient to predict the effect of each thermophysical property of the working fluid on the heat transfer resistance of a heat pipe. However, Eq. 43 shows a better performance and the

related confidence intervals / errors are smaller than Eq. 44. This shows the coefficients of Eq. 43 are better known and more accurate. Therefore, Eq. 43 is used for further analysis.

Changing the heat pipe just changes the coefficients but not the nature of the function nor the nature of dimensionless numbers. In addition, coefficients which start with a (i.e. a_1, a_2, a_3) are dimensionless while coefficients start with b (i.e. b_1, b_2, b_3) are in the same dimension and units of thermal resistance. Therefore, in case of any need for unit conversion, b_i coefficients may be converted accordingly.

As shown in Figure 19A, constant resistance surfaces can be defined. Based on Figure 19A, two main conclusions can be made. First, it is more difficult to improve the thermal resistance by improving thermophysical properties of the working fluid at lower thermal resistances, and second, at lower values of Π_1, Π_2 and Π_3, working fluid modification is more effective in terms of thermal resistance improvement. As a conclusion, for working fluid modification purpose it is desired to choose working condition or working fluid properties in a way to lower the value of proposed dimensionless numbers, especially in cases where modification of more than one working fluid property is possible.

Anyhow, if such a correlation holds for a wide range of real working fluids, rather than by arbitrary changing properties of water which does not correspond to any real working fluid, it would be possible to use the proposed set of reduced variables to predict the effect of molecular structure improvement on heat transfer characteristics of the heat pipe. This case is investigated in next section.

Effect of working fluid molecular size and structure on thermal resistance

In order to evaluate the effectiveness of the proposed set of reduced variables on total thermal resistance of the modelled heat pipe, 13 different working fluids (6 linear hydrocarbons, C_5H_{12} to $C_{10}H_{22}$, and 7 alcohols, CH_3OH to $C_7H_{15}OH$), which can operate at the design temperature of 50 °C, were chosen. Then the model was executed and the calculated thermal resistance versus the dependant reduced variable, Π_0, was plotted. As

shown in Figure 19B, as the molecular size of the working fluid increases the thermal resistance increases on perfect curves for each group of working fluids. This observation shows the presented set of reduced variables can be an effective tool in finding the objective set of fluids thermophysical properties and as a result can guide us toward optimizing the heat pipes working fluid by using new fluids or mixing two or more known fluids.

Contribution of each property on thermal resistance

In the next step, the fitted function (Eq. 43) is used to determine the effect of each thermophysical property on the thermal resistance of the heat pipe quantitatively. To do so, the thermal resistance is rewritten in the form of Eq. 45 by substituting dimensionless numbers with thermophysical properties of the working fluid.

$$R_{tot} = b_1 \sigma^{2a_1+a_2+2a_3} \mu_l^{-2a_1+a_2-a_3} h_{fg}^{-a_1} \rho_l^{-a_2} k^{-a_3} T^{-a_3} Q_{in}^{-a_2} \quad \textbf{Eq. 45}$$

The derivative of thermal resistance with each thermophysical property of the working fluid is calculated and the result is presented in form of the ratio of relative change in a thermophysical property over relative change in thermal resistance in Eq. 46 to Eq. 50.

$$\frac{\Delta \bar{R}_{tot}}{\Delta \bar{\sigma}} = 2a_1 + a_2 + 2a_3 \quad \textbf{Eq. 46}$$

$$\frac{\Delta \bar{R}_{tot}}{\Delta \bar{\mu}_l} = -2a_1 + a_2 - a_3 \quad \textbf{Eq. 47}$$

$$\frac{\Delta \bar{R}_{tot}}{\Delta \bar{h}_{fg}} = -a_1 \quad \textbf{Eq. 48}$$

$$\frac{\Delta \bar{R}_{tot}}{\Delta \bar{\rho}_l} = -a_2 \quad \textbf{Eq. 49}$$

$$\frac{\Delta \bar{R}_{tot}}{\Delta \bar{k}} = -a_3 \quad \textbf{Eq. 50}$$

where Δ operator is relative change in the property defined by Eq. 51

$$\Delta \overline{property} = d(property) / property \quad \textbf{Eq. 51}$$

As the analysis suggests, increasing thermal conductivity is the most important parameter while increasing viscosity is another important factor. However, as can be seen in Table 5 for water, decreasing surface tension is a better contributor than increasing viscosity since it has a larger value. Therefore, the ranking for the most effective modifications in the working fluid properties would be a combination of increasing and decreasing of thermophysical properties.

As summarized in
Table 6, the best actions for thermal resistance modification of a water-filled heat pipe would be increasing thermal conductivity, decreasing surface tension, decreasing latent heat, increasing viscosity, and decreasing liquid density, respectively. Therefore, the best working fluid modification method is the method that leads to this combination of changes in thermophysical properties.

However, since both capillary heat transfer limit and thermal resistance are important factors of heat pipe performance, it is worth to move in a direction where both an increase in CHF and a decrease in thermal resistance happen. For example, using diluted solutions of higher carbon number (≥ 4) alkyl alcohols is highly favourable because it decreases surface tension yet changes the surface tension gradient with temperature. The first effect is in favour of thermal resistance decrease and the second one is in favour of CHF increase.

Table 5- The numerical effect of each property on thermal resistance of the heat pipe filled with water

	σ	μ_l	h_{fg}	ρ_l	k
$\frac{\Delta \overline{R}_{tot}}{\Delta property}$	0.66	-0.14	0.37	0.12	-0.77

Table 6- Ranking of the proposed modifications for working fluid properties

Rank	Property	Action
1	k	↗
2	σ	↘

3	h_{fg}	↘
4	μ_l	↗
5	ρ_l	↘

In this example method is proposed is demonstrated for the analysis thermophysical properties of a heat pipe working fluid and a modified mathematical model based on a semi-analytical hydraulic approach is developed to investigate the applicability of the proposed method. After validation, the model was used to conduct an extensive sensitivity analysis on thermophysical properties of the working fluid. It is shown that the proposed set of dimensionless numbers can be successfully used to predict the effect of changing working fluid properties on the thermal resistance of the heat pipe. A monomial power function through a non-linear multivariate regression method is used to calculate unknown coefficients for water. It is found that it is more difficult to improve the thermal resistance by improving thermophysical properties of the working fluid in lower thermal resistances. Furthermore, in lower values of Π_1, Π_2 and Π_3, working fluid modification is more effective in terms of thermal resistance improvement. Without wishing to be bound by theory this could be due to the possibility that the exponents of monomial power function could carry relationships to geometric variables. Through further analysis of the fitted function the most effective working fluid optimization could be found. Increasing thermal conductivity, decreasing surface tension, decreasing latent heat, increasing viscosity, and decreasing liquid density are most effective modification of water properties in terms of improving thermal resistance of the exemplified heat pipe, respectively.

EXAMPLE 2

In this next example, a semi-dynamic model of concentric evacuated tube solar water heater is developed to investigate the effect of working fluid design on technical and economical performance of a typical solar water heater in a household located at Sydney, Australia.

The model is validated against experimental data. The effect of using water, ammonia, acetone, methanol, and pentane as working fluids of the built-in heat pipe is discussed comparatively during a typical day of operation. Water is identified as the best working fluid amongst the others. The variation of thermal resistance and critical heat flux of the heat pipes due to change in weather condition is presented and discussed. Then three hypothetical working fluids are proposed for further analysis which led to a working fluid design superior to water in performance. It is shown that the performance of the solar water heater can be significantly enhanced up to 28% and 50% from economical and technical points of view, respectively.

To have a reliable model which is able to provide realistic data for further analysis (daily/annual analysis of the performance/limitations), it is necessary to fully integrate a model of the built-in heat pipe with the Solar Water Heater (SWH) model.

The mathematical model for the concentric evacuated solar water heater consists of two sub-models. The first one is a dynamic sub-model which simulates the solar water heater. However, to have a rigorous model, built-in heat pipes are modelled in a separate static sub-model in which the thermal resistance of each heat pipe is calculated by solving a set of differential-algebraic equations. Then, the two models have been integrated as shown in Figure 20.

Dynamic Model

The most important set of equations that is used in the dynamic model of the concentric evacuated tube solar water heater is described in Eq. 52 to Eq. 57. The schematic diagram of the simulated system is shown in Figure 21.

$$M_g C_g \frac{dT_{g,i}}{dt} = S_p(\alpha_g + \rho_p \tau_g) \times G(t) + \frac{S_p \sigma}{\frac{1}{\varepsilon_p} + \frac{1-\varepsilon_g}{\beta \varepsilon_g}} \times (T_{p,i}^4 - T_{g,i}^4) + S_g \varepsilon_g \sigma \times (T_s(t)^4 - T_{g,i}^4) + \ldots$$

$$\ldots S_g h_a \times (T_a(t) - T_{g,i}) \qquad \text{Eq. 52}$$

$$M_p C_p \frac{dT_{p,i}}{dt} = S_p \alpha_p \tau_g \times G(t) + \frac{S_p \sigma}{\frac{1}{\varepsilon_p} + \frac{1-\varepsilon_g}{\beta \varepsilon_g}} \times (T_{g,i}^{\ 4} - T_{p,i}^{\ 4}) + \frac{1}{R_e\left(T_i^*, G(t)\right)} \times (T_i^* - T_{p,i}) \quad \text{Eq. 53}$$

$$M_c C_c \frac{dT_{c,i}}{dt} = S_c h_{f,i}\left(T_{f,i}, \dot{m}_{circulate}\right) \times (T_f - T_{c,i}) + \frac{1}{R_c\left(T_i^*, G(t)\right)} \times (T_i^* - T_{c,i}) \quad \text{Eq. 54}$$

$$M_f C_f \left(\frac{\partial T_f}{\partial t} + u_f \frac{\partial T_f}{\partial y} \right) = S_c h_{f,i}\left(T_{f,i}, \dot{m}_{circulate}\right) \times (T_{c,i} - T_f) - U_{loss,man.} S_{man.} \times (T_f - T_a) \quad \text{Eq. 55}$$

$$M_t C_f \frac{dT_t}{dt} = \dot{m}_{in} C_f \times (T_{f,N} - T_t) - (U_{loss,t} S_t + U_{loss,con.pipes} S_{con.pipes}) \times (T_t - T_a(t)) \quad \text{Eq. 56}$$

$$\frac{T_i^* - T_{c,i}}{R_c\left(T_i^*, G(t)\right)} = \frac{T_{p,i} - T_i^*}{R_e\left(T_i^*, G(t)\right)} \quad \text{Eq. 57}$$

$$\beta = \frac{S_g}{S_p} \quad \text{Eq. 58}$$

$$U_{loss,man.} = \frac{1}{\frac{D_{o,man.}}{D_{i,man.}} \frac{1}{h_i} + \frac{D_{o,man.}}{2k_{ins.}} \ln\left(\frac{D_{o,man.}}{D_{i,man.}}\right) + \frac{1}{h_a}} \quad \text{Eq. 59}$$

$$U_{loss,t} = \frac{1}{\frac{D_{o,t}}{2k_{ins.}} \ln\left(\frac{D_{o,t}}{D_{i,t}}\right) + \frac{1}{h_a}} \quad \text{Eq. 60}$$

$$Nu_D = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left(1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right)^{1/4}} \cdot \left(1 + \left(\frac{\mathrm{Re}}{28200}\right)^{5/8}\right)^{4/5} \quad \text{Eq. 61}$$

$$\mathrm{Re} = \frac{D_{i,h,man} V_f \rho_f}{\mu_f} \quad \text{Eq. 62}$$

$$T_s(t) = 0.0552 \times T_a(t)^{1.5} \quad \text{Eq. 63}$$

$$h_a = 5.7 + 3.8 \times V_a \quad \text{Eq. 64}$$

The assumptions inherited in the above equations are as follows:

- The evacuated tube solar water heater is divided to $5N+1$ nodes/lump sections: Cover glasses (N), the evaporator of heat pipes (N), the condenser of heat pipes

(N), the manifold pipe (N), the working fluid inside the heat pipes (N), and Water in the tank (1).

- Temperatures are uniform along each section of solar water heater.
- The conductive thermal resistance between solar plates and casing of the heat pipes is neglected. Therefore, the temperature of the solar plate is the same as temperature of evaporator section of heat pipe.
- Saturation temperature of the working fluid is calculated based on simple energy balance between evaporator and condenser sections of each heat pipe (**Eq. 57**).
- Each heat pipe is assumed to be in steady state in each time step duitng the numerical solution.
- Cover glass is assumed to be evacuated dual wall type. Therefore, there is no convective heat loss between the solar plate/absorber and the cover glass.
- The sky is clear so the sky temperature is estimated by Eq. 63.
- Air velocity is constant and is equal to 3 m/s.
- $\frac{\partial T_f}{\partial y}$ is discretized based on method of lines considering one node for each heat pipe.
- $h_{f,i}$ is calculated for each time step for each node while the Reynolds number is modified based on the hydraulic diameter of the manifold instead of the diameter of the condenser section (Eq. 61 and Eq. 62).
- The thermal resistance is a function of solar insolation and saturation temperature of the working fluid and is calculated for each heat pipe in each time step based on a hydrodynamic model which is developed and validated and discuss above.
- Circulating water flow distribution in the manifold, connecting pipes, and the tank is one dimensional, laminar, and uniformly distributed.
- The heat loss coefficient of connecting pipes is the same as that of the manifold and calculated by Eq. 59.
- The heat loss from the tank is calculated by Eq. 60, neglecting convection heat transfer inside the tank.

Static Model

A schematic diagram of the simulated heat pipe is shown in Figure 22. The modelling of the heat pipe is governed by a set of equations related to pressure drop in liquid and vapour phase of working fluid. The self-circulation of the working fluid inside the heat pipe is driven by the capillary pressure generated by micro-grooves. Therefore, for any location along the heat pipe, the capillary pressure is equal to pressure difference between liquid and vapour phase. The Laplace-Young equation is used to calculate this pressure difference (Eq. 12).

$$\frac{dP_v}{dz} - \frac{dP_l}{dz} = -\frac{\sigma}{r_{cr}^2(z)} \frac{dr_{cr}(z)}{dz} \qquad \textbf{Eq. 65}$$

Vapour and liquid pressure drop along heat pipe can be calculated from Eq. 13 and Eq. 14:

$$\frac{dP_v}{dz} = -\frac{2\mu_v C f_v \mathrm{Re}_v}{D^2_{v,h}} \frac{\dot{m}_v(z)}{A_{v,h}\rho_v} \qquad \textbf{Eq. 66}$$

$$\frac{dP_l}{dz} = -\frac{2\mu_l f_l \mathrm{Re}_l}{D^2_{l,h}} \frac{\dot{m}_l(z)}{NA_{l,h}\rho_l} \qquad \textbf{Eq. 67}$$

The assumptions used in modelling of heat pipe are:

- The gravitational pressure drop in liquid phase is neglected.
- The effect of filling ratio and accumulation of the working fluid at the end cap of the condenser section are also neglected.
- The evaporator and condenser section are under uniform heat flux condition.

Therefore, the mass flow rate can be calculated from Eq. 15. Consequently, the axial heat load distribution can be expressed by Eq. 69.

$$\dot{m}_l(z) = -\dot{m}_v(z) = -\frac{Q(z)}{h_{fg}} \qquad \textbf{Eq. 68}$$

$$Q(z)=\begin{cases}\dfrac{z}{L_e}Q_{in} & 0\le z\le l_e\\ Q_{in} & l_e<z<L_e+L_a\\ \dfrac{L_e+L_a+L_c-z}{L_c}Q_{in} & L_e+L_a\le z\le L_e+L_a+L_c\end{cases} \qquad \text{Eq. 69}$$

Results and Discussion

Validation

The developed dynamic model is evaluated against experimental data that is extracted from C.H. Bae, C. H. K., K.T. Chung, J.S. Suh (2006), *Prediction of Thermal Performance of Hot Water System with a Concentric Evacuated Tube Solar Collector using Axially Grooved Heat Pipe*, the 2006 WSEAS/IASME International Conference on Heat and Mass Transfer, Miami, Florida, USA.

The design data of the SWH and the built-in heat pipes are presented in Table 7 and

Table 8. The schematic diagram of the apparatus which is modelled in this study for the purpose of validation is shown in Figure 21. A comparison between the simulation results and experimental data are shown in Figures 23A, 23B and 23C. In addition, the accuracy of the model is evaluated by calculating the error percentage of simulated temperatures.

Table 7- Heat pipe details.

Wick structure	Casing	$D_{o,HP}[mm]$	$D_{i,HP}[mm]$	$L_e[m]$	$L_a[m]$	$L_c[m]$	N_g	$h_g[mm]$	$\frac{h_g}{\omega_2}$	$2\upsilon[^\circ]$
Grooved wick	Copper	8.67	7.17	1.25	0.12	0.13	30	0.5	1.1208	75.8

Table 8- Collector details.

Type	Tilt	$D_{o,g}[mm]$	$D_{i,g}[mm]$	$M_t[kg]$	$M_{mani.}[kg]$	$L_{mani}[m]$	$L_{con.pipes}[m]$	$k_{ins.}[wm^{-1}K^{-1}]$	D_t/L_t

	Angle								
Concentric evacuated tube	35	47	37	100	10	1	4	0.04	2

The simulations were executed for three different days at three different cooling water mass flow rates and three different inlet cooling water temperatures. As shown in Figures 23A, 23B and 23C, although there is a small difference between the experimental data and the simulated temperature of circulating water at the end of the manifold, the temperatures of water in the tank are very well predicted by the developed model. Furthermore, as shown in Figure 24, all of the predicted temperatures are within 95% confidence interval. The calculated error percentage for T_i is in the range of [-1.34%, 1.84%] with a total average of -0.06% and for $T_{f,N}$ is in the range of [-3.26%, 4.82%] with a total average of 0.34%. Therefore, it can be concluded that there is a very good agreement between the experimental data and the simulation results.

Effect of working fluid

In order to investigate the effect of working fluid on the operation of a concentric evacuated tube solar water heater, a scenario (Scenario-A) based on the requirements of a 5 member family is defined. The schematic diagram of the simulated system is shown in Figure 25. In this scenario, a total number of 20 heat pipes is considered in the solar water heater and the circulating water mass flow rate varies on hourly basis based on hot water consumption pattern of a typical household presented in K. T. PAPAKOSTAS, N. E. P., B. A. SOTIROPOULOS (1995). "Residential Use Patterns In Greece." Solar Energy 54(6): 369-374. Typical weather data for the first day of January at Sydney, Australia is used in this analysis as graphically shown in Figure 26.

Thermal resistance

One of the major aspects of any heat pipe mediated system is the thermal resistance of the built-in heat pipe. It would be of high interest to understand how changing working fluid

affects thermal behavior of a heat pipe which is installed in an evacuated tube SWH during the day. Study of this effect also guides the choice of the best and most suitable working fluid. To be able to analyze this aspect of heat pipes, the variation of condenser, evaporator, and total thermal resistance of one of the built-in heat pipes (HP_{10}) are shown in Figure 27.

As shown in Figure 27, for water filled heat pipes, the thermal resistance of the evaporator section decreases as solar insolation and therefore saturation temperature of the built –in heat pipe increases. However, the results suggest a different trend of variation of thermal resistance in the condenser section. It is interesting to note that, the total thermal resistance of the heat pipe remains almost the same during the day. This behaviour is explained by considering the hydrodynamic of working fluid within the heat pipe. As solar insolation increases, the input heat to the heat pipe increases which results in higher gradient of the working fluid level in each section of the heat pipe. While the level of the working fluid in the evaporator section decreases, to transfer higher heat loads to the condenser section, the level of working fluid in the condenser increases due to accumulation of working fluid at the end cap of the condenser. However, the notable point is the increase in the condenser thermal resistance almost compensates the decrease in the evaporator thermal resistance.

However, what is important in terms of the working fluid selection, is how other working fluids behave in the same situation. To investigate this case, four most widely used working fluids, Acetone, Methanol, Pentane, and Ammonia, are selected for comparison against water. The results of the simulations for total thermal resistance of the heat pipes filled with the four mentioned working fluids relative to water are presented in Figure 28.

In Figure 28, the gray dashed line shows total thermal resistance of the heat pipe filled with water. Other lines show thermal resistance of the same heat pipe filled with other working fluids relative to water. As can be seen in Figure 28, total thermal resistance of all other working fluids are notably higher than that of water. Ammonia shows a different behaviour when the thermal resistance suddenly decreases between 9 hr and 15 hr. This behaviour makes it the best working fluid in comparison to other three ones in the peak hours of solar

insolation in terms of total thermal resistance. Pentane is ranked as the worse working fluid and Methanol as the most stable one during the day.

Heat transfer capacity

The other major aspect of every heat pipe included system is the Critical Heat Flux (CHF) of the built-in heat pipe. CHF basically means how much heat is transferable using a specific heat pipe at a specific saturation temperature of a specific working fluid. In other words, CHF is the heat transfer limit of a heat pipe. Basically, when the input heat exceeds the CHF, the heat pipe faces dry-out condition and stops working. This means the working fluid cannot return back from the condenser to the evaporator section. As a result, total thermal resistance of the heat pipe drastically increases since hydrodynamic circulation of the working fluid inside the heat pipe terminates. Therefore, it is highly favorable to have heat pipes with higher CHF. This is achievable by modifying the geometrical properties of heat pipes and modifying the working fluid thermophysical properties.

To investigate the effect of working fluid properties on CHF, first CHF of water during the day is calculated and shown in Figure 29.

As shown in Figure 30, the CHF of the heat pipe highly increases during peak hours of solar insolation. This behaviour is closely related to temperature dependence of working fluid properties. In other words, as saturation temperature increases, due to higher solar insolation rates, the thermo-physical properties change in favourite of the CHF increase. However, the case is not the same for all working fluids. For example, Ammonia shows a completely different behaviour. To be able to compare this phenomenon, the CHF of the four previously mentioned working fluids relative to water is shown in Figure 30. In Figure 30, gray dashed-line is normalized critical heat flux of water.

In Figure 30, the gray dashed line shows the normalized CHF of the heat pipe filled with water. Other lines show the CHF of the same heat pipe filled with other working fluids relative to water. As can be seen in Figure 30, all mentioned working fluids have higher CHF relative to water at first and last hours of the day. However, during sunny hours of the

day all of them have significantly lower critical heat fluxes relative to that of Water. The absolute values of the CHF for the modelled heat pipe for four mentioned working fluids are shown in Figure 31.

As can be seen in Figure 31, Ammonia again shows a different behaviour when the CHF starts to drastically decrease at the first hours of the day. Then it starts to increase until 12hr and again decreases until 15 hr. This behaviour makes Ammonia the most non-stable working fluid in comparison to other three ones as far as the CHF is concerned. Methane with a stable increase in the CHF is the best and most stable working fluid. Acetone and Pentane are in lower rank than Methane, respectively.

However, the impact of the working fluid properties on the critical heat flux in the solar water heater context needs further attention. To analyse this phenomena, the results of the CHF calculation for Ammonia and Water for each of the 20 heat pipes of the solar water heater are presented in Figure 32. The following discussion is valid for any other working fluid. Water and Ammonia are chosen here solely for explanation purposes.

In Figure 32, the CHF of each 20 heat pipes of the evacuated tube solar water heater is calculated separately. The light-grey lines show the CHF of the heat pipes which are filled with Ammonia and the dark-grey lines show the CHF of the heat pipes which are filled with Water. The solid line with the black bubbles shows the instantaneous/momentary amount of transferred heat in each time step during the day for HP_{10} in watts. For other heat pipes, the transferred heat does only changes slightly. To have a fully functioning heat pipe the CHF must be higher than the instantaneous/momentary transferred heat. In other words, to have the solar water heater function perfectly, the transferred heat for all of the 20 heat pipes need to be lower than the relevant CHF.

As shown in Figure 32, the pattern of change in the CHF and the value of the CHF during the day are totally different for Water in comparison to Ammonia. For Water, the first heat pipe in the manifold (HP_1) has the lowest CHF while for Ammonia the last heat pipe

(HP_{20}) has the lowest CHF. In addition, as time passes and solar insolation increases, the CHF of Ammonia filled heat pipes decreases while for Water filled heat pipes, the CHF increases. This phenomenon basically means for Ammonia only first two heat pipes start up successfully and continue to operate during the day. All other heat pipes face dry-out condition anytime between 10hr and 16 hr and they become operational again after 16hr. But for Water just the first three heat pipes terminate at peak hours of day. Other 17 heat pipes can continue operating until the end of the day. However, one should bear in mind that basically if heat pipe i fails to operate, any other heat pipe that is located after heat pipe i ($HP_{i+1} \ldots HP_N$) also fails to operate. Therefore, failure of a heat pipe means huge loss of solar energy due to consequent failure of later ones.

Overall, by optimizing the working fluid total thermal resistance of heat pipes reduces and as a result efficiency of the solar water heater increases. This means at a specific solar insolation higher amount of heat is transferable to the hot water tank. Simultaneously, the CHF of the heat pipes which is closely related to the maximum heat capacity of the solar water heater increases. This means possibility of system failure during the year decreases. As the result, by using an improved working fluid in a typical solar water heater it would be possible to harvest considerably higher amount of solar energy.

Although this aspect of working fluid optimization for heat pipes is the most important one, it is not investigated in the literature. It is worth to clearly mention here that this complex phenomenon is much more important than any other one. In working fluid optimization or heat pipe design, failing to consider the effect of the CHF violation on the performance of the SWH leads to significant decrease in solar fraction of the solar water heater. However, as mentioned above, all actions that can be taken to improve the CHF (except that of related to thermal conductivity), works against improvement of the thermal resistance. Therefore, to achieve the best overall performance the solar water heater, and optimization problem the thermophysical properties of the working fluid needs to be determined.

To be able to combine and consider both of the mentioned aspects of optimization, defining an objective function in the form of systems economy seems suitable. Since the simulation model is fairly complex to apply classic optimization techniques on, Global Optimization techniques (Genetic Algorithm and Pattern search Algorithm) are used for optimization purposes.

Hypothetical working fluids

The results of the optimization problem using two mentioned algorithm ended up in two hypothetical fluids, respectively Hyp_1 and Hyp_2. In addition, a comprehensive sensitivity analysis is carried out to find out how far the results of optimization are from the global optimum. The result of the sensitivity analysis led us to Hyp_3. The averaged properties of these three hypothetical working fluids are shown in Table 9.

Table 9- Average properties of the hypothetical working fluids.

	h_{fg}	ρ_l	k	μ_l	σ	$\Pi_1/\Pi_{1,water}$ *	$\Pi_2/\Pi_{2,water}$	$\Pi_3/\Pi_{3,water}$	$Merit / Merit_{Water}$
Hyp_1	2.45E6	884	0.649	7.00E-5	0.0726	54.2	0.2	9.0	7.4
Hyp_2	2.45E6	971	0.644	9.86E-5	0.0727	27.4	0.3	6.4	5.8
Hyp_3	2.45E6	741	0.678	9.44E-5	0.0668	25.3	0.3	5.4	4.2

Since in this example water has shown the best performance with the lowest thermal resistance and highest CHF among other investigated real fluids, water is treated as the basis for further comparison. The dynamic model is run for Scenario-A for each hypothetical working fluid. The results are presented in Figure 33 and Figure 34. Again the gray dashed lines show normalized thermal resistance and CHF of water.

As shown in Figure 33, the optimized hypothetical working fluids have lower total thermal resistance relative to water in sunny hours of the day at least by 6% and the estimated CHF is higher than that of water by 40.8%, 40%, and 27.5% for Hyp_1, Hyp_2, and Hyp_3,

respectively. Therefore, from technical point of view the performance of the built-in heat pipes are significantly improved.

Impact on economy

Apart from the technical benefits of working fluid optimization in a solar water heater, what is clear is how the working fluid optimization benefits the end users and the manufacturers of such devices. Since the end users and the manufacturers compile price signals very well, it is worth showing the effect of using optimized working fluid in forms of costs and revenues.

To do this, calculation of the improvement in produced Small Scale Technology Certificate (STC) seems to be the best approach. The STC for an evacuated solar water heater can be estimated by Eq. 70 and the improvement in the generated STCs can be calculated by Eq. 71.

$$STC = Maximum Capacity \times Solar\ Zone\ Rating \times Current\ Solar\ Multiplier \times ... \quad ...Life Time\ of\ SWH \qquad \textbf{Eq. 70}$$

$$Improvement = \frac{STC_{Hyp}}{STC_{Water}} \times 100 \qquad \textbf{Eq. 71}$$

Daily analysis

To perform the improvement calculations on daily basis, since only the working fluid is changed in Scenario-A, Eq. 71 can be reduced to Eq. 72.

$$Improvement = \frac{Maximum Capacity_{Hyp_i}}{Maximum Capacity_{Water}} = \frac{Q_{transfered.new,Hyp_i}}{Q_{transfered,Water}} \times \frac{CHF_{Hyp_i}}{CHF_{Water}} \times 100 \qquad \textbf{Eq. 72}$$

The results of the above analysis can be summarized as: applying Hyp_1, Hyp_2, and Hyp_3 results in 57.9%, 56.7%, and 38.9% improvement in produced STC in a typical day, respectively. However, to gain more realistic rate of improvement, one needs to simulate

the solar water heater with different working fluids for a Typical Meteorological Year and calculate the improvement in STC production on annual basis.

Annual analysis

To conduct the analysis on annual basis some few changes were applied to the model to reflect the actual condition better. A schematic diagram of the simulated SWH is shown in Figure 35. Consequently, Eq. 56 is replaced with Eq. 73. The typical methodological data of Sydney from Renewable Energy (Electricity) Regulations, Regulation 19B 2012 is used for simulations. After running the simulation for Water and Hyp_3 as working fluid, the maximum transferred heat in each day of the year is calculated and plotted in Figure 36 in watts. The maximum transferred heat is the maximum instantaneous/momentary amount of heat that is transferred from the solar absorbers to the manifold. The black and grey dashed-lines in Figure 36 are the CHF of Water and Hyp_3, respectively.

$$M_t C_f \frac{dT_t}{dt} = \dot{m}_{circulate} C_f \times (T_{f,N} - T_t) + \dot{m}_{in} C_f \times (T_{in} - T_t) - \ldots (U_{loss,t} S_t + U_{loss,con.pipes} S_{con.pipes}) \times (T_t - T_a(t)) \quad \text{Eq. 73}$$

As can be seen in Figure 36, in some days during the year maximum transferred heat in solar water heater exceeds the CHF of the built-in heat pipes. This violation of the CHF means the solar water heater stops working and as the result the process of heat transfer from solar absorbers to hot water tank fails. The effect of the CHF violation remains in the system until the whole system including the evaporator section of the heat pipes cools down. In other words, the heat pipes will start up again in the next day which results in huge loss of solar energy.

In Figure 37, the amount of lost energy due to violation of the CHF limitation and the number of days in which failure occurs are shown. Figure 37 also shows failure happens in fewer days for Hyp_3 in comparison to Water. For Water no heat pipe failure occurs between days 87 and 261 while for Hyp_3 the range is wider (between days 69 and 272). Apart from the number of the days in which failure happens, Figure 37 also suggests that the amount of lost energy in each failure day is different for each working fluid. Therefore,

it is obvious that modifying the working fluid highly affects the performance of the solar water heater during a typical year mainly by shifting CHF of the heat pipes. A same comparison can be done between two other mentioned hypothetical fluids and water.

To make the comparison more convenient, a new parameter called Failure Ratio on daily and hourly basis is proposed, as show in Eq. 74 & Eq. 75. In addition, the contribution of working fluid modification in STC production is determined by calculating the number of STCs that is recovered by modifying the working fluid (Eq. 76). Solar fraction is also calculated for each working fluid using Eq. 77. The results of this quantitative analysis are summarized in

Table 10 and

Table 11.

$$FR_d = \frac{Number\ of\ failure\ days}{365} \qquad \textbf{Eq. 74}$$

$$FR_h = \frac{\sum_{i=1}^{Number\ of\ failure\ days}\left(24 - t_{failure,i}\right)}{8760} \qquad \textbf{Eq. 75}$$

$$STC\ recovery = \frac{STC_{Hyp_1} - STC_{Water}}{STC_{Water}} \times 100 \qquad \textbf{Eq. 76}$$

$$f = \frac{Q_{Solar}}{Q_{Deman}} \qquad \textbf{Eq. 77}$$

Table 10- Summarized results of annual analysis (Absolute values).

Working fluid	FR_h	FR_d	Cumulative Lost Energy [J year^{-1}]	f	10 year savings [MWh]	Produced STC [$]
Water	0.2033	0.3589	3.73E9	0.2769	18.09	434
Hyp_1	0.0351	0.0658	5.81E8	0.4107	26.83	644

Hyp_2	0.0335	0.0630	5.64E8	0.4115	26.88	645
Hyp_3	0.1040	0.1890	1.89E9	0.3542	23.14	555

Table 11- Summarized results of annual analysis (improvement percentage relative to Water).

Working fluid	FR_h	FR_d	Cumulative Lost Energy	f	10 year savings	STC Recovery
Hyp_1	82.73	81.67	84.42	48.32	48.31	48.39
Hyp_2	83.52	82.45	84.88	48.61	48.59	48.62
Hyp_3	48.84	47.34	49.33	27.92	27.92	27.88

As shown in **Table 11**, different criteria suggest different rates of improvement. However, each criterion reflects different sets of information. For instance, FR_h, FR_d, and f solely reflect the performance of solar water heater from technical point of view while STC recovery reflects economical aspects along with technical aspects. Demand information (household requirement for hot water) is included in f while FR_h, FR_d, and Produced STC are solely related to the solar water heater.

The absolute value of f and Produced STC are affected by requirements that are imposed by standards of hot water supply (for example, some standards require the minimum temperature of 45°C for hot water delivery or 1 STC equals 1MWh of renewable energy generation) but FR_h, FR_d are solely related to the operation and design of SWH.

Therefore, it can be concluded that criteria like f and Produced STC are affected by local regulations. This fact makes it difficult to compare different technology which are produced and tested in different locations in the world. In addition, interpretation of two

mentioned parameters is difficult for non-technical users. However, the new proposed criteria fill this gap and provide the users with a simple, universal, and comparable value.

As **Table 11** suggests, from technical point of view almost 49% improvement is achievable by using Hyp_3 as working fluid. This value corresponds to almost 28% improvement in the produced STC. However, Hyp_1 and Hyp_2 perform much better. Using Hyp_1 will result in almost 83% and 48% improvement in FR_h and the produced STC, respectively. Using Hyp_2 improves the performance even more. Furthermore, it is shown in **Table 10** and **Table 11** that although the absolute values of f are not representative in terms of technical performance of SWH, the relative improvement in f has strong correlation with the STC recovery. This means, when comparing different working fluids in similar environmental and regulatory conditions, solar fraction can be used as a reliable criteria for quantifying economical aspects of the system.

In this example, a fully integrated model for a grooved type evacuated tube solar water heater is developed and validated against experimental data. The validated model is used for working fluid modification. Three modified hypothetical working fluids were used to measure the impact of working fluid change in a real evacuated tube solar water heater.

It is shown that the proposed evaluation methods can be used successfully. In addition, it is shown that considerably higher performance of solar water heater (up to 84%) is easily achievable by solely improving the working fluid properties. Also modifying the working fluid may lead to about 50% improvement in the economy of the solar water heater.

EXAMPLE 3

In this example the thermophysical properties of a working fluid are determined using a mathematical model of a microgroove heat pipe in evacuated tube solar water heater application that is dependant upon on the thermophysical properties of the working fluid.

Optimizationn Algorithm

In this example, the optimization problem is run for two modes. In the first mode, temperature independent mode, the purpose of the optimization is to find a real fluid which has the closest mean liquid phase properties to that of the global hypothetical optimum fluid. In the second mode, temperature dependant mode, a design temperature based on the temperature profiles obtained from a dynamic simulation of evacuated tube solar water heater is defined. The working fluid properties including the vapour phase properties are optimized at that design temperature, which is 120C in this case. Again the final goal of optimization is to find a mixture of predefined real fluids which has the closest mean properties to that of the global hypothetical optimum fluid. Therefore, two main differences exist between the two studied modes: dependence/independence of working fluid properties on temperature, and including/excluding vapour phase properties in optimization problem.

The optimization problem in each mode is divided in two more steps. The first step to find the optimal values for fluid properties, and the second step is to find a mixture of real fluids that matches the optimized properties best. Pattern Search and Genetic Algorithm are applied to the first step in order to find the best algorithm and to make sure the final solution is a global one. However, for the second step only GA is applied due to restrictions that are inherited in PS method. A more detail description is provided below.

Temperature independent (mean liquid phase properties)

The optimization problem for mean liquid phase properties has been carried out in two steps: the first step is to find the optimal average properties of the liquid phase and the second step it to find a mixture of different components that make such properties. Therefore, there are two separate optimization problems to deal with.

- For the first optimization problem, three different global optimization algorithms, Simulated Annealing, Genetic Algorithm, and Pattern Search, have been tested to find the best mean liquid phase properties of the working fluid. The performance of SA was not satisfactory for this problem therefore the results are not presented here. GA and PS provided good responses in finding the optimal values.

- For the second step, a lookup table consisting of 25 most common fluids in heat transfer has been created. GA is applied to the problem to find the best combination of the 25 working fluid targeting the prior stage results. For this step, average properties have been used and mixtures are assumed to be ideal. Therefore, the properties of the liquid phase of the mixture are calculated by Eq. 78.

$$property_{mix} = \sum x_i \times property_i \qquad \text{Eq. 78}$$

Temperature dependant (vapour and liquid phase properties at design temperature)

The procedure that is used in this mode is similar to the previous mode. However some important differences exist as below:

- For the first step, vapour phase properties are also considered. In addition, optimization is run at 120C. Therefore, temperature dependence of working fluid properties is considered.
- For the second step, a lookup table consisting of the same 25 most common fluids in heat transfer has been created. GA is applied to the problem to find the best combination of the 25 working fluids targeting the results of the prior stage. In order to include the mixing effect, the optimization code is integrated to HYSYS process simulation software through COM server. NRTL equitation of state through Aspen plus databank is chosen. Therefore, deviation from ideality in both liquid and vapour phase is taken into account.

Objective Function and restriction

Temperature independent (mean liquid phase properties)

Generally, by optimizing the working fluid we expect to see that total thermal resistance of the built-in heat pipes reduces and as a result efficiency of the solar water heater increases. On the other hand, we expect to witness an increase in the CHF of the heat pipes which is closely related to the maximum heating capacity of the solar water heater. Therefore, by

using an improved working fluid in a typical solar water heater it would be possible to harvest considerably higher amount of solar energy.

However, as mentioned above, all actions that can be taken to improve the CHF, works against improvement of the thermal resistance. However, thermal conductivity is an exception in this case since based on the applied theoretical model the CHF solely depends on hydrodynamic behaviour of the working fluid. Anyhow, to be able to combine and consider both of the mentioned aspects of optimization, defining an objective function in the form of systems economy seems suitable. Therefore, for the first optimization problem the objective function is the operating costs of the SWH as defined in Eq. 79 and the aim to minimize the objective by manipulating the mean thermophysical properties of liquid phase, which are σ, h_{fg}, k, μ_l, and ρ_l. The limits for thermophysical properties of liquid phase are defined based on the maximum and minimum of mean values of the properties for the considered working fluids in the temperature range of [10,120] (Eq. 80).

For the second optimization problem, which is to find the best components and compositions of the working fluid, the objective function is set to be the sum of square of the properties ratio over target values which represents the closeness of the working fluid properties to the target/optimised values (Eq. 81). For this problem, the decision variables are the components ID and the mole fractions of each component in the working fluid. The restrictions are shown in Eq. 82.

$$obj = C_{elec.} \times (Q_D - Q_{trans}) + C_{elec} Q_D \times \max[0, (\max(Q_{trans}) - CHF)]^2 \qquad \textbf{Eq. 79}$$

Subject to:

$$0.0015 < \sigma < 0.0728$$
$$0.27E6 < h_{fg} < 2.444E6$$
$$0.12 < k < 0.683$$
$$0.07E\text{-}3 < \mu_l < 1.7E\text{-}3$$
$$374 < \rho_l < 998$$

Eq. 80

$$obj_{property} = \sum \left(\frac{property_{opt} - property_{mix}}{property_{opt}} \right)^2 \quad \text{Eq. 81}$$

Subject to:

$$0 \le x_i \le 1 \quad \text{Eq. 82}$$

Temperature dependant (vapour and liquid phase properties at design temperature)

The only difference that exists in this mode in comparison to the previous mode is related to upper and lower limits for each thermophysical properties. The limits for thermophysical properties of liquid phase are defined based on the maximum and minimum of the properties for the considered working fluids at 120C. The limits are shown in Eq. 83. The objective function for the first and second optimization step in this mode are the same as the temperature independent mode.

Subject to:

$$0.00368 < \sigma < 0.0243$$
$$127E3 < h_{fg} < 2200E3$$
$$0.0607 < k < 0.684$$
$$0.0486E\text{-}3 < \mu_l < 0.669E\text{-}3 \quad \text{Eq. 83}$$
$$7.86E\text{-}6 < \mu_v < 22.2E\text{-}6$$
$$374 < \rho_l < 1290$$
$$0.445 < \rho_v < 206$$

Results and Discussion

Temperature independent (mean liquid phase properties)

Thermophysical properties

The trends of the optimization using each one of the mentioned methods are shown in Figure 38 and Figure 39. Each method is run several times to make sure the optimal values are not local optima. For PS several starting points have been selected as shown in **Table 12**. However, as shown in Figure 38, the result of the optimization problem is only slightly affected by varying the starting point. In addition, several runs of GA with

different sets of random first generations also show very slight difference in the optimal value of objective function (see Figure 39). In other words, the probability of reaching the global optima is very high in this optimization problem. Therefore, it can be concluded that for the temperature independent problem, PS and GA optimization methods seem to be suitable. However, the optimization problem is very sensitive to the form of objective function. It is worth noting that the results of GA are marginally better than that of PS yet they require more iterations and consequently longer CPU-time to find the optimal values (1500 vs. 500 iterations, respectively). The final values of thermophysical properties for each run are shown in **Table 13**.

Table 12- Starting point of each run for PS method.

Run	h_{fg}	ρ_l	k	μ_l	σ
#1	2.00E+06	700	0.150	1.00E-03	0.0728
#2	3.00E+05	400	0.150	1.00E-04	0.0020
#3	2.40E+06	900	0.680	7.00E-05	0.0020
#4	2.40E+06	374	0.122	7.00E-05	0.0500

Table 13- Optimal thermophysical properties resulted from applying PS and GA.

	Run	h_{fg}	ρ_l	k	μ_l	σ	Objective function
Pattern Search	#1	2.44E+06	864	0.459	1.25E-04	0.0728	-0.833
	#2	2.43E+06	898	0.550	1.00E-04	0.0719	-0.810
	#3	2.44E+06	681	0.655	7.00E-	0.0726	-0.833

					05		
	#4	2.45E+06	884	0.649	7.00E-05	0.0726	-0.856
	#1	2.31E+06	957	0.634	1.25E-04	0.0713	-0.671
	#2	2.45E+06	971	0.644	9.86E-05	0.0727	-0.856
GA	#3	2.45E+06	971	0.644	9.86E-05	0.0727	-0.856
	#4	2.43E+06	953	0.474	1.48E-04	0.0724	-0.810
	#5	2.43E+06	953	0.474	1.48E-04	0.0724	-0.810

Analysing the final optimized properties for each run provides us with some insight into liquid phase optimization. For latent heat, thermal conductivity, surface tension, and liquid phase density optimizer (GA/PS) tends to choose values that are close to the upper limits. But the case for liquid phase viscosity is different while the optimizer chooses values that are close to the lower limit. This is consistent with the concept of figure of merit (Eq. 42). It means the optimizer tries to increase CHF as much as possible. The main reason for this behaviour is there is a huge cost penalty for heat pipes failure which is an order of magnitude bigger than the penalty for loosing thermal resistance for heat pipes. However, when comparing very similar working fluids the mentioned figure of merit is not very accurate.

$$Figure\ of\ Merit = \frac{\rho_l \sigma h_{fg}}{\mu_l} \qquad \textbf{Eq. 84}$$

Composition

The results of the previous section are hypothetical working fluids with optimized properties which are still far from the real world. However, the optimized properties can

guide use through optimizing the working fluid in real world. To do so, among the properties that are mentioned in

Table 13, the result of the second run of GA (GA #2) is used as the target values due to its best objective function. Using the methodology described above, some options for the real working fluid are estimated by running the second step optimization problem. The objective function is as presented in Eq. 81 and the results are shown in

Table 14.

Table 14- Components and composition of the optimized real fluids for temperature independent mode

Number of Components	Component #1	Component #2	Composition #1	Composition #2	Objective function*
	22	21	0.13	0.87	1.6355
	22	21	0.13	0.87	1.6355
2	22	21	0.13	0.87	1.6355
	22	21	0.13	0.87	1.6355
	21	22	0.77	0.23	1.6355

* Objective function value for pure water is 13.8297.

The best objective function that can be achieved theoretically is zero. Considering the calculated objective function for pure water (which is 13.8297) suggests that the adding some additives to water can make it much closer to the optimal working fluid in terms of liquid phase properties. The results propose that components 22 and 21 are definitely the best components that suit the target values. However, there is a little variation in the compositions which suggests a requirement for running a detailed optimization problem using the dynamic model directly by just choosing these two components to find the best global compositions. It is worth reminding that for the second step of optimization the optimizer is restricted to choose just 2 components. Other number of components is also tried (3 and 4 components). However, the optimizer tends to choose the same combination of components repeatedly.

Temperature dependant (vapour and liquid phase properties at design temperature)

Thermophysical properties

The trends of the optimization using each one of the mentioned methods are shown in Figure 40. For PS, several starting points have been selected as shown in **Table 15**. Again, as shown in Figure 40, the result of the optimization problem is only slightly affected by varying the starting point. In addition, GA is also reached to the same final point. Therefore, it can be concluded that for the temperature dependent problem, PS and GA optimization methods also seem to be suitable. However, same as temperature independent mode, PS reaches to the final value much faster than GA. The final values of thermophysical properties for each run are shown in **Table 16**.

Table 15- Starting point of each run for PS method.

Run	h_{fg}	ρ_l	k	μ_l	σ	ρ_v	μ_v
#1	1E6	1E2	1E-1	1E-3	1E-2	1E2	1E-4
#2	2.20E6	1.29E3	6.84E-1	6.69E-4	2.43E-2	2.06E2	2.22E-5
#3	1.27E5	3.74E2	6.07E-2	4.86E-5	3.68E-4	4.45E-1	7.86E-6

Table 16- Optimal thermophysical properties resulted from applying PS and GA.

	Run	h_{fg}	ρ_l	k	μ_l	σ	ρ_v	μ_v	Objective function
Pattern Search	#1	2.19E6	1286	0.6250	0.000544	0.0241	195.3	9.3E-6	-7.37227
	#2	2.2E6	1290	0.6332	0.000554	0.0243	182.1	10.9E-6	-7.37221
	#3	2.2E6	1290	0.6631	0.000049	0.0243	1.1	7.9E-6	-7.37234
GA	#1	1.22E6	1225	0.1818	0.000198	0.0184	32.3	10.7E-6	-7.3710

As can be concluded from

Table 16, for liquid phase properties again the optimizer engine tries to manipulate the properties towards increasing the figure of merit. For the vapour phase, the optimizer tends to choose lower viscosity and higher density. For the next step of this mode the results of PS #1 are chosen as target values.

Composition

The results of component and composition optimization (the second step) using GA are presented in

Table 17.

Table 17- Components and composition of the optimized real fluids for temperature dependent mode

Number of Components	Component #1	Component #2	Component #3	Composition #1	Composition #2	Composition #3	Objective function
2	22	5	-	0.85	0.15	-	2.5366
	22	5	-	0.97	0.03	-	2.5366
	6	22	-	0.29	0.71	-	2.0229
	22	5	-	0.85	0.15	-	2.5366
	22	6	-	0.52	0.48	-	2.0228
	6	22	-	0.49	0.51	-	2.0228
	22	6	-	0.51	0.49	-	2.1581
3	22	6	7	0.51	0.40	0.08	2.0402
	6	7	22	0.46	0.03	0.51	2.0299

* Objective function for pure water is 2.6127

In this case also different number of components were chosen to do the optimization. As shown in

Table 17, again the two component fluids are performing better than more complicated fluids. Although the optimizer chooses different set of components as the final solution there are two things to mention here: first, component 22 is always among the best set;

second, there is one lighter fluid (like component 5, 6, or 7) to modify the properties of component 22. In this case, considering the value of objective function for water, which is 2.6127, we see that the final solutions are always better than water but not as much as they were in temperature independent mode. The main reason is the vapour properties of water at the design temperature, which shows the importance of vapour phase properties in choosing the working fluid. This aspect is completely ignored by literature in working fluid optimization of heat pipes. However, 22/6 set always performs better than 22/5 set for two component fluids. Adding more components to the mixture does not necessarily make the final fluid better.

Comparison between temperature dependant/independent modes

To find out to what extent the final proposed composition is effective, annual analysis has been carried out. For both modes, the dynamic model is integrated to thermodynamic models that exist in Aspen-HYSYS to calculate the thermophysical properties of the working fluid mixture. To have a similar ground for comparison, for temperature independent mode, the vapor properties calculated by Aspen-HYSYS are ignored and replaced by mean vapor properties of water vapor. However, changes in liquid phase composition due to evaporation are taken into account. Then, the technical results of annual analysis are compared with the results of pure water.

For temperature dependent mode, all the thermophysical properties are calculated by Aspen-HYSYS. In addition, vapor phase properties of the mixture are taken into account. Again the technical results of annual analysis have been compared to the results of pure water. The results of the comparison reflect the effectiveness of the described working fluid design technique discussed herein.

However, because huge computational effort is required to run the simulations for a whole year, we compared the performance of the different working fluids on daily basis. The results of these runs would be like Figure 28 for thermal resistance and Figure 31 for CHF.

Conclusion

In this example, the thermophysical properties working fluid in an evacuated tube solar water heater are optimised in two different modes focusing on temperature dependence and the effect of vapour phase properties. The final optimized real mixtures of common fluids always included component 22 (water) as one of the main components. This shows component 22 is a perfect base fluid however adding some other fluids leads to much better performance. Using the real mixtures proposed by temperature dependant and independent modes in the dynamic model shows the overall economic of the system can be improved by 30% and 45%, respectively. Therefore, the proposed method is very effective in screening a huge number of potential fluids and picking the best components for further optimization. In addition, the method can propose an initial composition for the best set of components to start doing experimental test in an experimental pilot.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

Appendix A

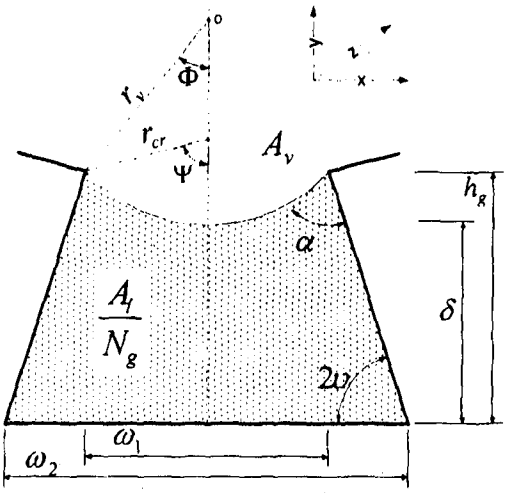


Figure A- 1 Schematic of a microgroove cross-section

The micro-groove cross section is shown in Figure A- 1.

$$\Psi = \arcsin\left(\frac{\omega_1}{2r_{cr}}\right) \qquad \textbf{Eq. A- 1}$$

$$\Phi = \arcsin\left(\frac{\omega_2}{D_v}\right) \qquad \textbf{Eq. A- 2}$$

Based on the definitions of angles Ψ and Φ in eq. Total liquid and vapour cross section area can be calculated as follows:

$$A_v(z) = \pi r_v^2 + N_g\left(r_{cr}(z)^2\,\Psi(z) - r_v^2 + \frac{\omega_1 r_v \cos(\Phi(z))}{2} - \frac{\omega_1 r_{cr}(z)\cos(\Psi(z))}{2}\right) \qquad \textbf{Eq. A- 3}$$

$$A_l(z) = N_g\left(h_g\left(\frac{\omega_1+\omega_2}{2}\right) + \frac{\omega_1 r_{cr}(z)\cos(\Psi(z))}{2} - r_{cr}(z)^2\,\Psi(z)\right) \qquad \textbf{Eq. A- 4}$$

Therefore, hydraulic radius of liquid and vapour channel are defined as:

$$D_{h,l}(z) = \frac{4\frac{A_l(z)}{N_g}}{\omega_2 + 2\sqrt{\left(\frac{\omega_2-\omega_1}{2}\right)^2 + h_g^2}} \qquad \textbf{Eq. A- 5}$$

$$D_{h,v}(z) = \frac{4A_v(z)}{2\pi r_v - 2N_g r_v \Phi(z) + 2N_g r_{cr}(z)\Psi(z)} \qquad \textbf{Eq. A- 6}$$

And the elevation of the liquid in grooves and contact angle of liquid in micro region can be calculated from Eq. A- 7 and Eq. A- 8, respectively.

$$\delta(z) = h_g - r_{cr}(z)\left(1 - \cos(\Psi(z))\right) \quad \textbf{Eq. A- 7}$$

$$\alpha(z) = \pi - \Psi(z) - 2\upsilon \quad \textbf{Eq. A- 8}$$

Other applied equations are as follows:

$$D_v = D_i - 2h_g \quad \textbf{Eq. A- 9}$$

$$D_o = D_i + 2t_{wall} \quad \textbf{Eq. A- 10}$$

$$\omega_1 = \frac{\pi D_v}{2N_g} \quad \textbf{Eq. A- 11}$$

$$\omega_2 = 2h_g \cot(2\upsilon) + \omega_1 \quad \textbf{Eq. A- 12}$$

$$\omega_{fin} = \frac{\frac{\pi D_v}{N_g} - \omega_1}{2} \quad \textbf{Eq. A- 13}$$

$$\omega_o = \frac{\pi D_o - 2N_g\omega_{fin}}{N_g} \quad \textbf{Eq. A- 14}$$

$$t_{fin} = \frac{D_i - D_v}{2} \quad \textbf{Eq. A- 15}$$

Nomenclature

A	Area (m^2)
a	Coefficient defined in Eq.
b	Coefficient defined in Eq.
C	Coefficient of Poiseuille number
CHF	Critical Heat Flux (W)
D	Diameter (m)
$f\,\mathrm{Re}$	Poiseuille number
h	Height (m)
h_{fg}	Latent neat ($J\,Kg^{-1}$)
k	Thermal conductivity ($W\,m^{-1}C^{-1}$)
L	Length (m)
$\dot{m}$	Mass flow rate ($Kg\,s^{-1}$)
Ma	Match number
N	Number
P	Pressure (Pa)
PDI	Pressure Drop Index ($m^2\,s$)
Q	Heat (W)
R_t	Thermal resistance (CW^{-1} or mCW^{-1})
r	Radios (m)
R	Gas constant ($J\,Kg^{-1}K^{-1}$)
Re	Reynolds number
$RMSE$	Root Mean Square Error
T	Temperature (C)
t	Thickness (m)
z	Length (m)

Greek Symbols

Π	Dimensionless number
σ	Surface tension (m^2)
α	Contact angle (m^2)
ρ	Density (m^2)
Ψ	Meniscus radios angle (m^2)
Φ	Vapour channel radios angle ($^\circ$)
2υ	Groove wall inclination angle ($^\circ$)
μ	Viscosity ($Pa.s$)
γ	Specific heat ratio
δ	Liquid thickness (m)
ω_{fin}	Groove fin width (m)
ω_1	Groove opening width (m)
ω_2	Groove base width (m)
ω_o	Groove outer width (m)

Subscripts

a	adiabatic section
c	condenser section / capillary
ca	capillary axial
cr	capillary radial
e	evaporator section
f	working fluid
$film$	micro thin liquid film
fin	groove fin
g	groove
h	hydraulic
in	input
l	liquid
mic	micro region
min	minimum
o	outer
s	substrate
sat	saturation
tot	total
v	vapour
$wall$	heat pipe wall
$\bar{}$	average value

Nomenclature

S	Area (m^2)
err	Error percentage
Pr	Prandtl number
C	Specific heat ()
CHF	Critical Heat Flux (W)
D	Diameter (m)
f Re	Poiseuille number
h	Height (m) / Convection heat transfer coefficient ($W m^{-2} C^{-1}$)
h_{fg}	Latent neat ($J Kg^{-1}$)
k	Thermal conductivity ($W m^{-1} C^{-1}$)
L	Length (m)
$\dot{m}$	Mass flow rate ($Kg s^{-1}$)
M	Mass
N	Total number of heat pipes/grooves/days
P	Pressure (Pa)
G	Solar insolation ($W m^{-1}$)
Q	Heat (W)
R_t	Thermal resistance (CW^{-1} or mCW^{-1})
r	Meniscus radios
Nu	Nusselt number
Re	Reynolds number
U	Total heat transfer coefficient ($W m^{-2} C^{-1}$)
T	Temperature (C)
t	Time
z	Length (m)
V	Velocity ($m s^{-1}$)
HP	Heat pipe
SWH	Solar Water Heater
f	Solar fraction
FR	Failure ratio

Greek Symbols

Π	Dimensionless number
σ	Surface tension (m^2) / Stefan–Boltzmann constant
α	Absorbance
ρ	Density (m^2) / Reflectance
ε	Emissivity
2υ	Groove wall inclination angle (°)
μ	Viscosity ($Pa.s$)
β	Surface area ratio
ω_2	Groove base width (m)

Subscripts & Superscripts

$sim.$	simulation
a	adiabatic section / air
c	condenser section / capillary
ca	capillary axial
cr	capillary radial
e	evaporator section
p	solar absorber
d	daily basis
i	inner / counter
g	cover glass / groove
h	Hydraulic / hourly basis
in	input
l	liquid
$con.pipes$	connecting pipes
t	tank
o	outer
$cir.$	circulation fluid inside manifold
$man.$	manifold pipe
f	circulation fluid inside manifold
$ins.$	insulation
s	sky
D	diameter
tot	total
v	vapour
*	saturation
Hyp	hypothetical fluid

The claims:

1. A method of determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system:

performing a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein one or more thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

performing a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from a known fluid list, wherein one or more thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the working fluid for the assembly.

2. The method according to any one of the preceding claims, wherein the step of the processing system manipulating the thermophysical properties of the fluid mixture includes manipulating:

a number of fluids selected from the known fluid list to form the fluid mixture;

a selection of fluids from the known fluid list to form the fluid mixture; and

a proportion of each selected fluid in the fluid mixture.

3. The method according to any one of the preceding claims, wherein the mathematical model is dependent upon:

performance criteria; and

temporal heat source data.

4. The method according to claim 3, wherein the processing system obtains at least one of the performance criteria and the temporal heat source data at least partially based upon input data from a user.

5. The method according to any one of the preceding claims, wherein the method includes the processing system manipulating the thermophysical properties of the modelled working fluid within a range of thermophysical properties defined by the fluids in the known fluid list.

6. The method according to any one of the preceding claims, wherein the method includes the processing system minimising the discrepancy between the thermophysical properties of the fluid mixture and the hypothetical fluid by manipulating the thermophysical properties of the fluid mixture during the second optimisation process, wherein the fluid mixture having the thermophysical properties which result in a minimalised discrepancy is determined by the processing system as the working fluid.

7. The method according to any one of the preceding claims, wherein the method includes the processing system receiving input data indicative of a selection of the mathematical model from a library of mathematical models for a plurality of assemblies.

8. The method according to any one of the preceding claims, wherein at least one of the first optimisation process and the second optimisation process is performed using one of the following optimisation algorithms:

genetic algorithm; and

pattern search.

9. The method according any one of the preceding claims, wherein the one or more thermophysical properties are selected from vapour and/or liquid phase thermophysical properties.

10. The method according to any one of the preceding claims, wherein the thermophysical properties are selected from: thermal conductivity, viscosity, surface tension, latent heat of evaporation, density, specific heat capacity, vapour pressure, and isentropic expansion factor/heat capacity ratio.

11. The method according to any one of the preceding claims, wherein the assembly involving the transfer of thermal energy between a heat source and a heat sink is selected from a heat pump, a heat pipe or an apparatus including one or more heat pumps and/or heat pipes.

12. The method according to any one of the preceding claims, wherein the assembly is used in an application including: heat pumps including solar heat pumps; heat pipes; solar thermal including solar water heaters, solar cooling and solar ovens; chipset cooling including CPU and GPUs; permafrost cooling; cooking; ventilation heat recovery in air condition systems; refrigeration; cooling and dehumidification in HVAC; heat pipe heat exchangers; spacecraft thermal control; and, thermal transfer in energy storage including batteries and thermal storage fluids.

13. The method according to any one of the preceding claims, wherein the first objective function is one of: an economic objective function, a techno-economic objective function, and a technical objective function.

14. The method according to claim 13, wherein the first objective function is selected from: minimizing the operating cost of the assembly, minimizing the capital cost of the assembly, the net present value and combinations thereof.

15. The method according to any one of the preceding claims, wherein the mathematical model of the assembly includes the effect of hydrodynamics of the modelled working fluid on one or more of the following: the thermal resistance of the assembly; the critical heat flux of the assembly; and the thermal failure ratio of a built-in heat pipe/heat pump in the assembly.

16. The method according to any one of the preceding claims, wherein the mathematical model of the assembly includes a reduction in the dimension of the domain of the mathematical model through the use of dimensionless numbers.

17. A method according to any one of the preceding claims, wherein the known fluid list includes one or more of the following: acetone, 2,2-dimethyl propane, isobutene, n-butane, 2-methyl butane, n-pentane, n-hexane, n-heptane, cyclo-pentane, cyclo-hexane, benzene, chloroform, acetone, chlorine, ammonia, water, 1-pentanol, iso-butanol, acetadol, methanol, ethanol, isopropyl alcohol, 3,3-dimethyl-1-butene, di-chloro mono-flouro methane, ethylene oxide and propylene oxide.

18. The method according to any one of the preceding claims, wherein the method includes providing the assembly using the determined working fluid.

19. A processing system for determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

perform a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

perform a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from an known fluid list, wherein thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the working fluid for the assembly.

20. The processing system according to claim 19, wherein the processing system is

configured to perform the method of any one of claims 1 to 17.

21. A system for providing an assembly including a working fluid for transferring thermal energy between a heat source and a heat sink, wherein the system includes:

the processing system according to claim 19 or 20; and

a plant to provide the assembly including the working fluid.

22. A computer readable medium for configuring a processing system to determine a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer readable medium includes executable instructions which when executed configures the processing system to:

perform a first optimization process in relation to a first output of a first objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are iteratively manipulated to optimise the first output, thereby determining thermophysical properties of a hypothetical fluid; and

perform a second optimization process in relation to a second output of a second objective function dependent upon the thermophysical properties of the hypothetical fluid and thermophysical properties of a fluid mixture comprising a plurality of fluids selected from an known fluid list, wherein thermophysical properties of the fluid mixture are iteratively manipulated to optimise the second output, thereby determining the working fluid for the assembly.

23. The computer readable medium according to claim 22, wherein the computer readable medium configures the processing system to perform the method of any one of claims 1 to 17.

24. A method of determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system performing steps of:

performing an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized; and

comparing the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

selecting, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

25. A processing system for determining a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

perform an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized; and

compare the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

select, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

26. A computer readable medium for configuring a processing system to determine a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer readable medium includes executable instructions which when executed configures the processing system to:

perform an optimization process in relation to an output of an objective function dependent upon a mathematical model of the assembly, wherein thermophysical properties

of a modelled working fluid of the mathematical model are manipulated in the optimization process to determine thermophysical properties of a hypothetical fluid when the output is optimized; and

compare the thermophysical properties of the hypothetical fluid against data set of thermophysical properties of known fluids; and

select, based on the results of the comparison, one of the known fluids from the data set as the working fluid which has thermophysical properties closest to the thermophysical properties of the hypothetical fluid.

27. A method of determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, the method including the following steps:

providing a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determining one or more objective functions associated with the mathematical model of the assembly; and

manipulating a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

28. The method according to claim 27 wherein the one or more thermophysical properties of the working fluid are selected from vapour and/or liquid phase thermophysical properties.

29. The method according to claim 27 or 28 wherein the thermophysical properties are selected from: thermal conductivity, viscosity, surface tension, latent heat of evaporation, density, specific heat capacity, vapour pressure, and isentropic expansion factor/heat capacity ratio.

30. The method according to any one of claims 27 to 29, wherein the assembly

involving the transfer of thermal energy between a heat source and a heat sink is selected from a heat pump, a heat pipe or an apparatus including one or more heat pumps and/or heat pipes.

31. The method according to any one of claims 27 to 30 wherein the assembly involving the transfer of thermal energy between a heat source and a heat sink is used in an application including: heat pumps including solar heat pumps; heat pipes; solar thermal including solar water heaters, solar cooling and solar ovens; chipset cooling including CPU and GPUs; permafrost cooling; cooking; ventilation heat recovery in air condition systems; refrigeration; cooling and dehumidification in HVAC; heat pipe heat exchangers; spacecraft thermal control; and, thermal transfer in energy storage including batteries and thermal storage fluids.

32. The method according to any one of claims 27 to 31 wherein the objective function associated with the mathematical model includes one or more of the following: economic objective functions, techno-economic objective functions, and/or technical objective functions.

33. The method according to claim 32 wherein the objective function is selected from: minimizing the operating cost of the assembly, minimizing the capital cost of the assembly, the net present value and combinations thereof.

34. The method according to any one of claims 27 to 33 wherein the mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid includes the effect of hydrodynamics of the working fluid on one or more of the following: the thermal resistance of the assembly; the critical heat flux of the assembly; and the thermal failure ratio of the built-in heat pipe/heat pump in the assembly.

35. The method according to any one of claims 27 to 34 wherein the mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid includes a reduction in the dimension of the domain of the mathematical

model through the use of dimensionless numbers.

36. The method according to any one of claims 27 to 35 including the further step of comparing the one or more thermophysical properties of the working fluid which meet the objective function against a data set of one or more thermophysical properties of one or more known working fluids.

37. The method according to claim 36 wherein the known working fluids include one or more of the following: acetone, 2,2-dimethyl propane, isobutene, n-butane, 2-methyl butane, n-pentane, n-hexane, n-heptane, cyclo-pentane, cyclo-hexane, benzene, chloroform, acetone, chlorine, ammonia, water, 1-pentanol, iso-butanol, acetadol, methanol, ethanol, isopropyl alcohol, 3,3-dimethyl-1-butene, di-chloro mono-flouro methane, ethylene oxide and propylene oxide

38. The method according to claim 36 or claim 37 including the subsequent step of selecting a working fluid from the one or more known working fluids which includes one or more thermophysical properties that match closest to the one or more thermophysical properties of the working fluid which meet the objective function.

39. The method according to claim 36 or claim 37 including the subsequent step of selecting a mixture of the one or more known working fluids which includes one or more thermophysical properties that match closest to the one or more thermophysical properties of the working fluid which meet the objection function.

40. A method of determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the method includes a processing system perform the steps of:

providing a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determining one or more objective functions associated with the mathematical model of the assembly; and

manipulating a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

41. A processing system for determining one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the processing system is configured to:

provide a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determine one or more objective functions associated with the mathematical model of the assembly; and

manipulate a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

42. A computer readable medium for configuring a processing system to determine one or more thermophysical properties of a working fluid for use in an assembly involving the transfer of thermal energy between a heat source and a heat sink, wherein the computer readable medium includes executable instructions for configuring the processing system to:

provide a mathematical model of the assembly dependent upon the one or more thermophysical properties of the working fluid;

determine one or more objective functions associated with the mathematical model of the assembly; and

manipulate a value of the one or more thermophysical properties within the mathematical model until the one or more objective functions is optimised and thereby determine the one or more thermophysical properties of the working fluid which meet the one or more objective functions.

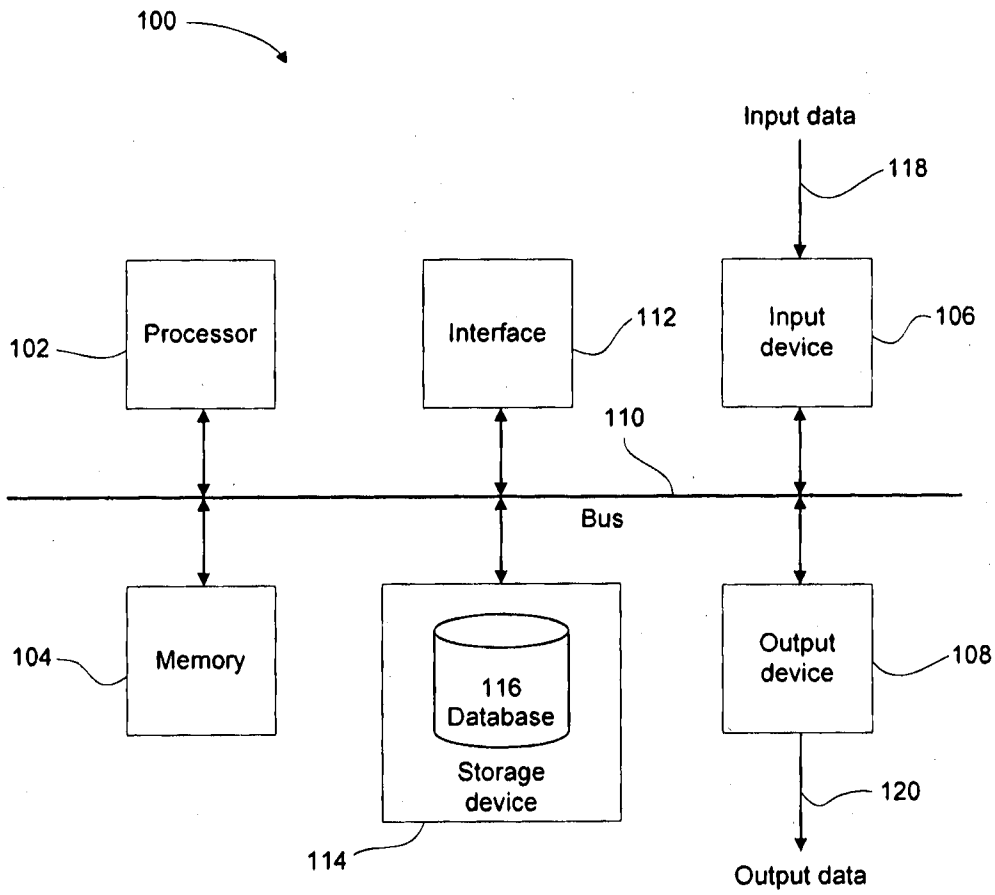

100
Input data
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Processor
102
Interface
112
Input device
106
110
Bus
Memory
104
116 Database
Storage device
114
Output device
108
120
Output data

FIGURE 1

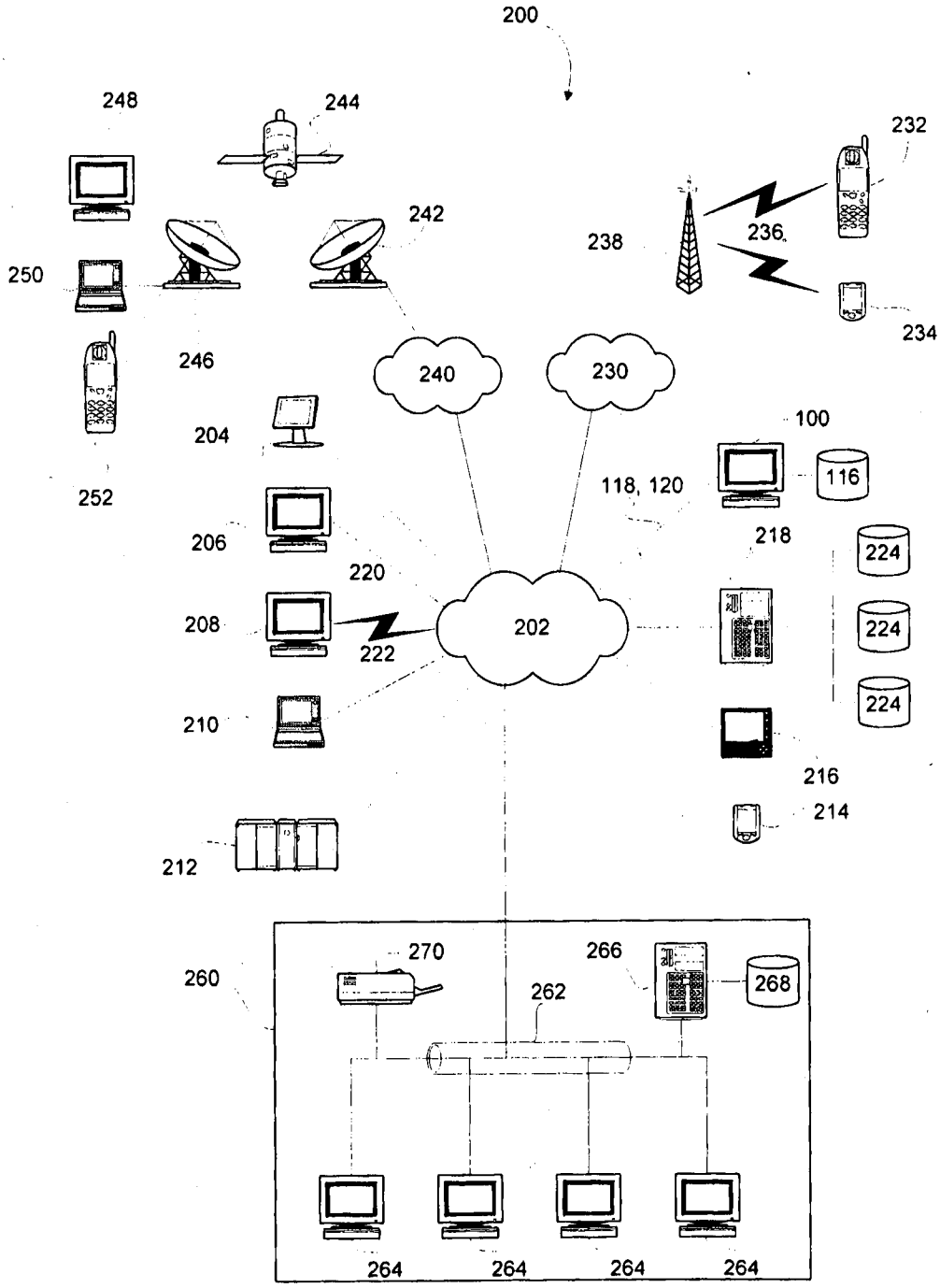

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FIGURE 2

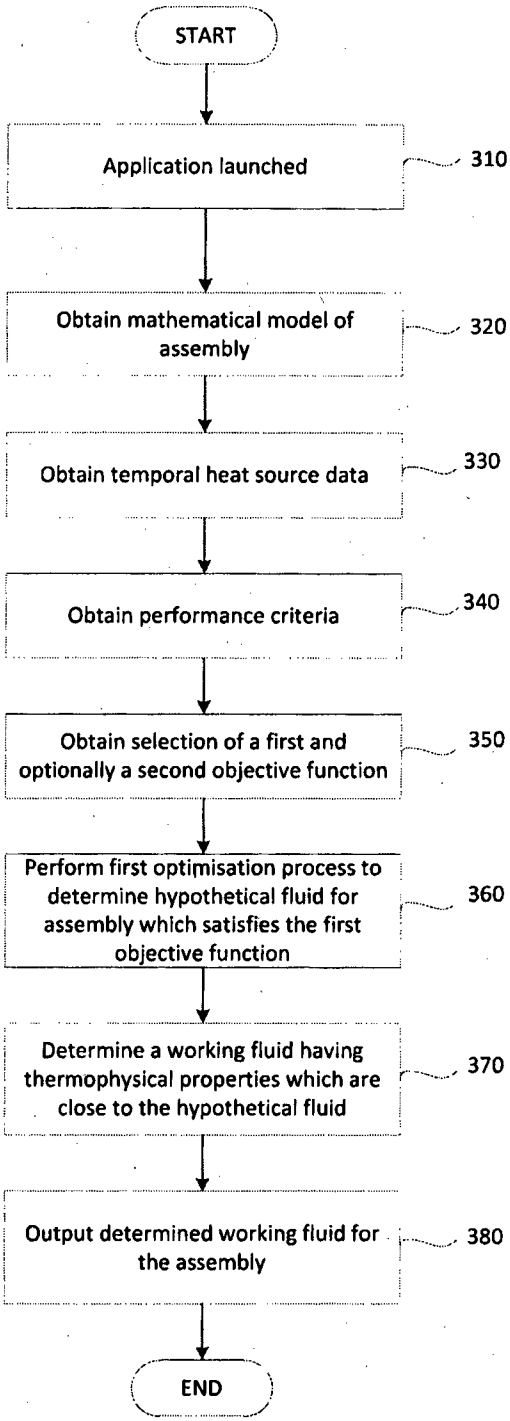

START
Application launched
310
Obtain mathematical model of assembly
320
Obtain temporal heat source data
330
Obtain performance criteria
340
Obtain selection of a first and optionally a second objective function
350
Perform first optimisation process to determine hypothetical fluid for assembly which satisfies the first objective function
360
Determine a working fluid having thermophysical properties which are close to the hypothetical fluid
370
Output determined working fluid for the assembly
380
END

FIGURE 3

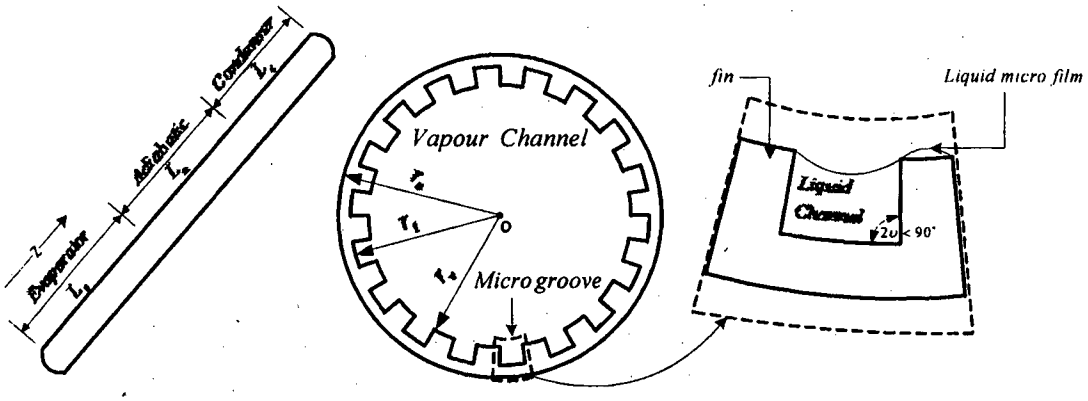


FIGURE 4

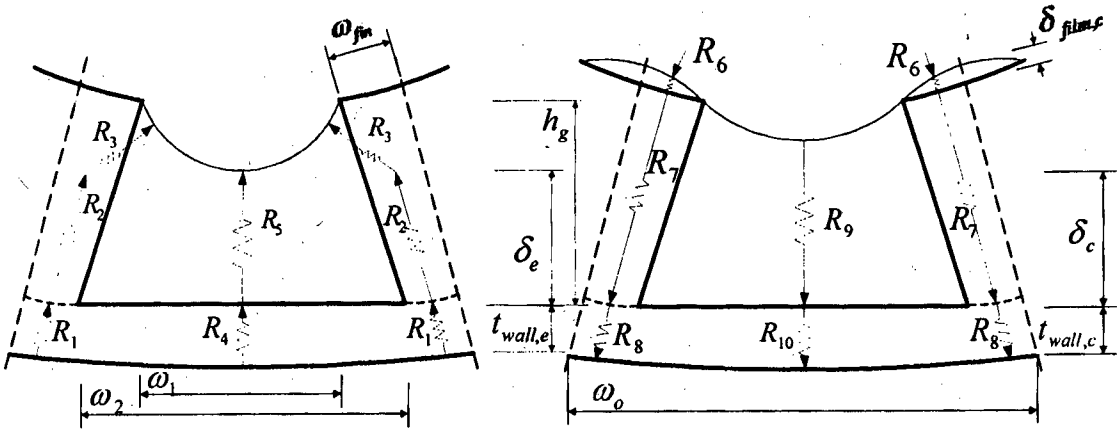


FIGURE 5

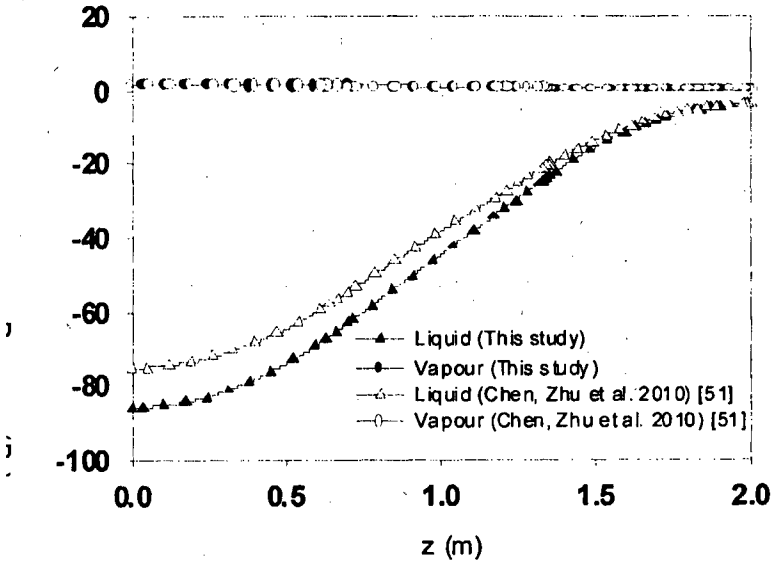


FIGURE 6

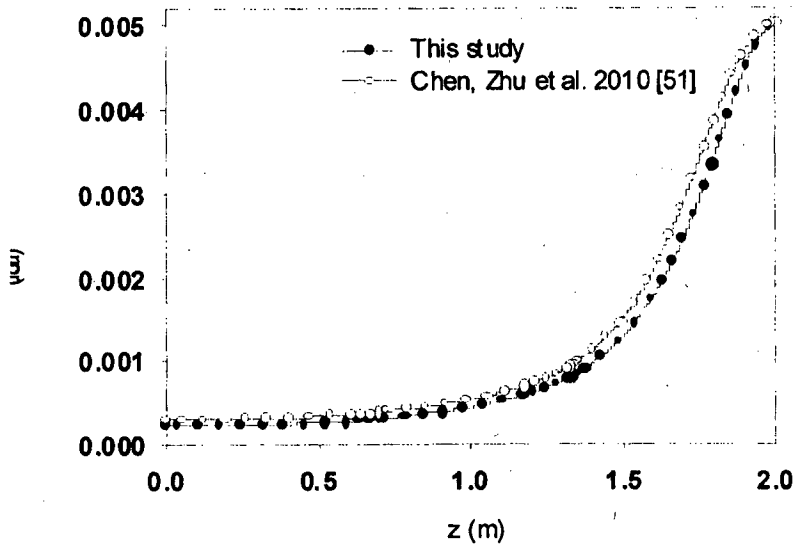


FIGURE 7

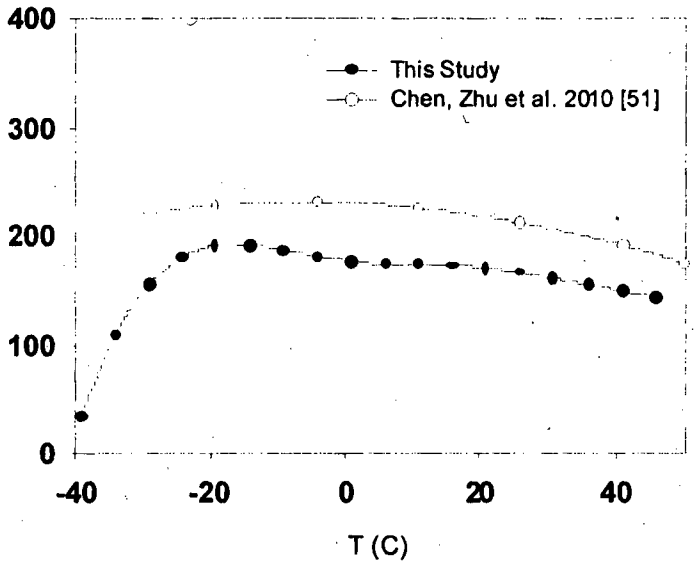


FIGURE 8

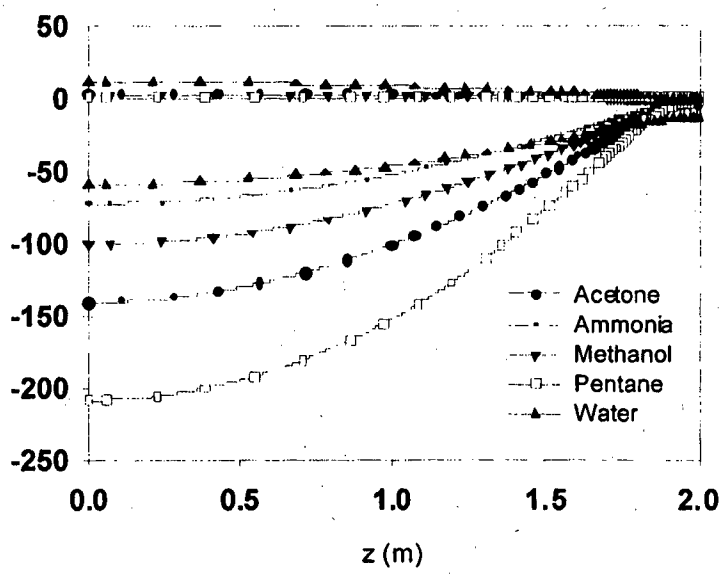


FIGURE 9

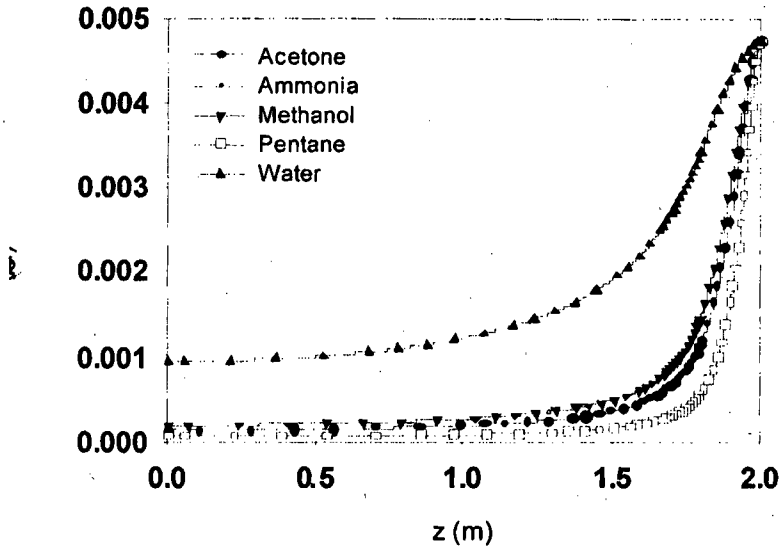


FIGURE 10

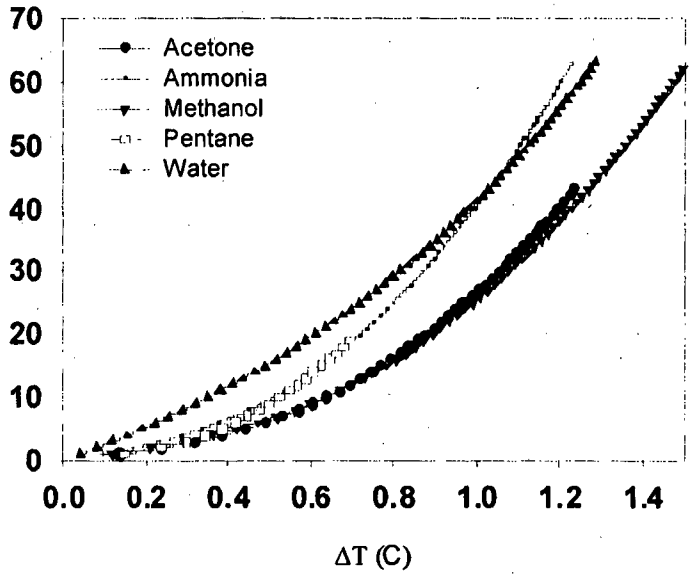


FIGURE 12

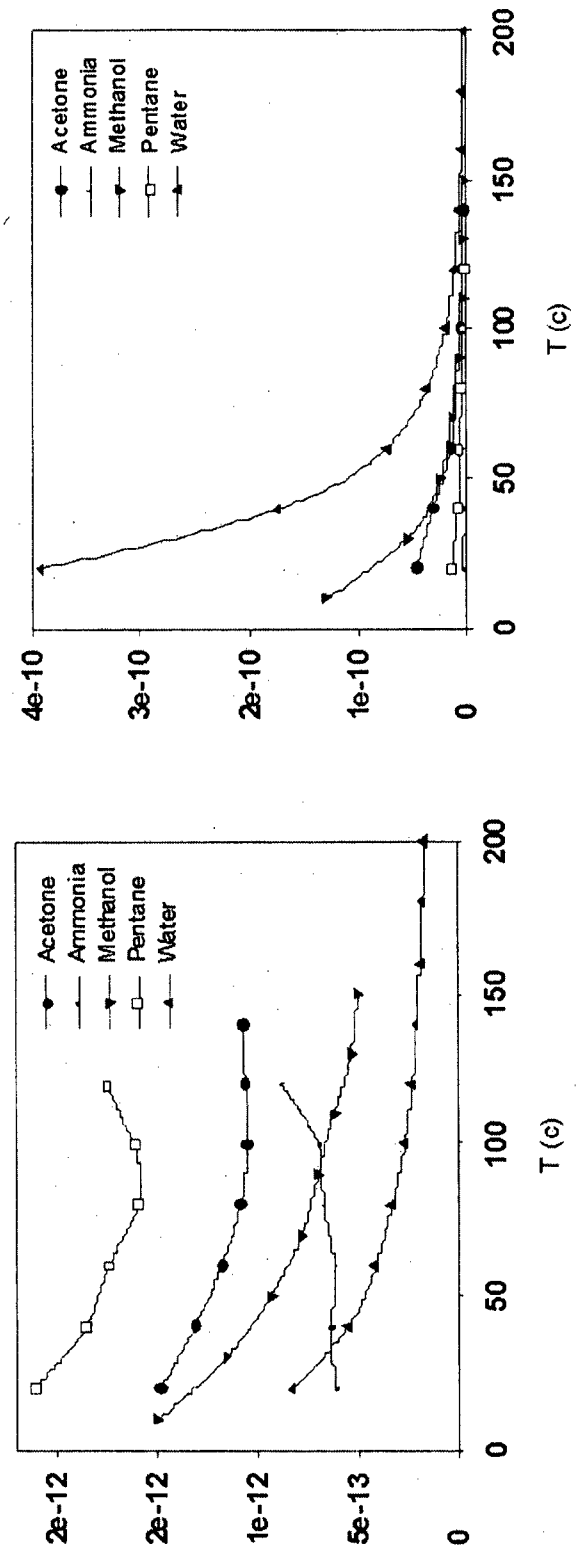

Acetone
Ammonia
Methanol
Pentane
Water
T (c)
0
50
100
150
200
0
5e-13
1e-12
2e-12
2e-12
0
1e-10
2e-10
3e-10
4e-10

FIGURE 11

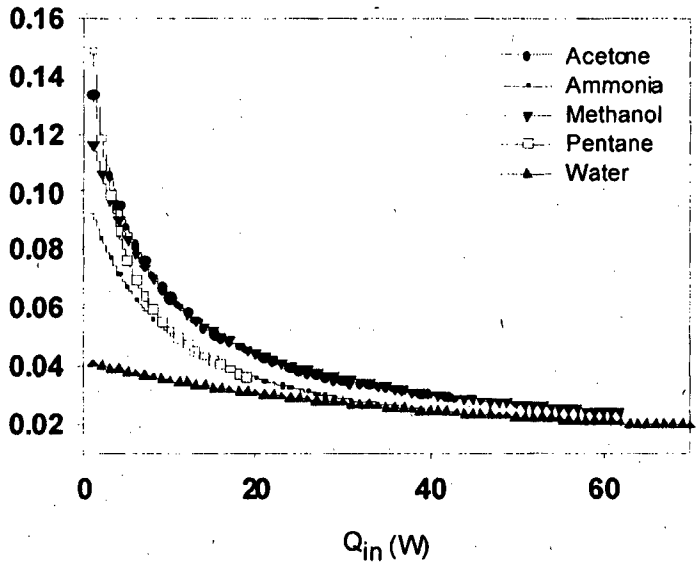


FIGURE 13

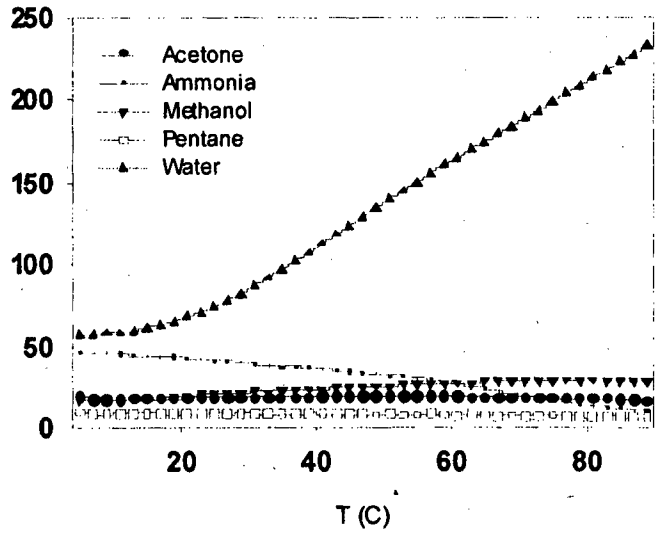


FIGURE 14

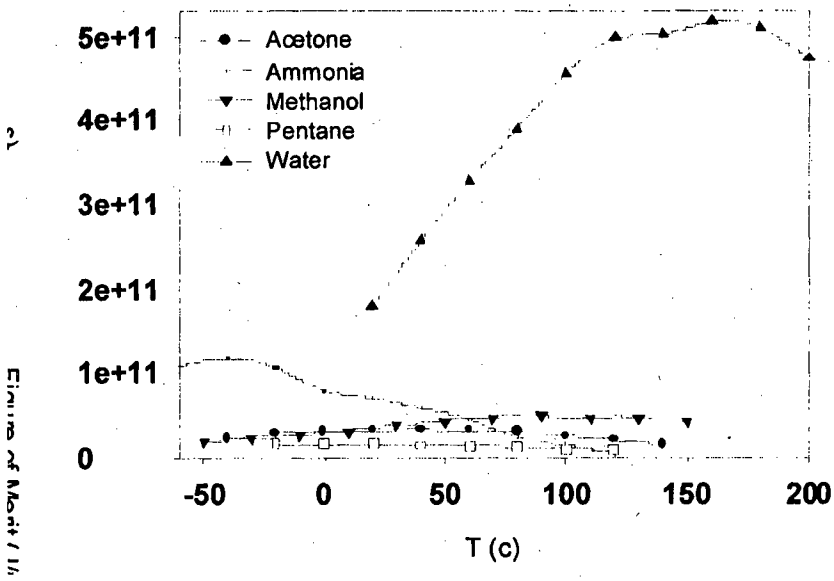


FIGURE 15

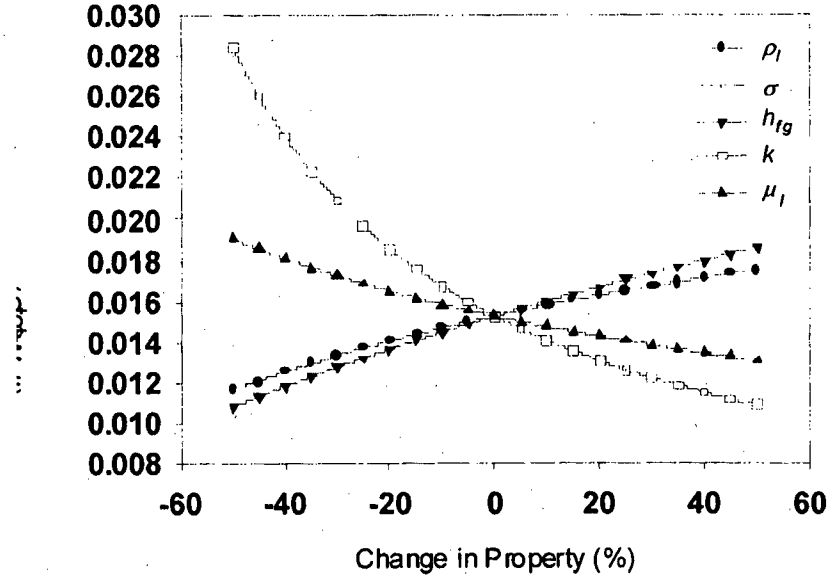


FIGURE 16

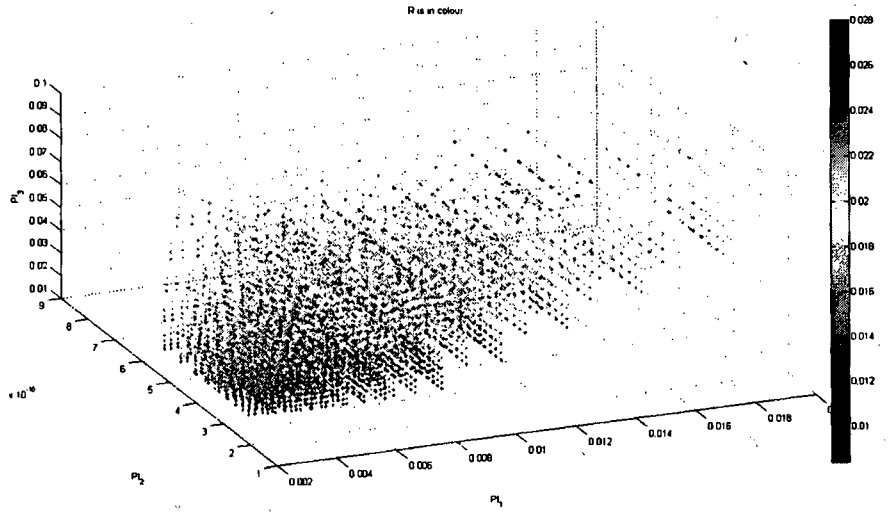


FIGURE 17A

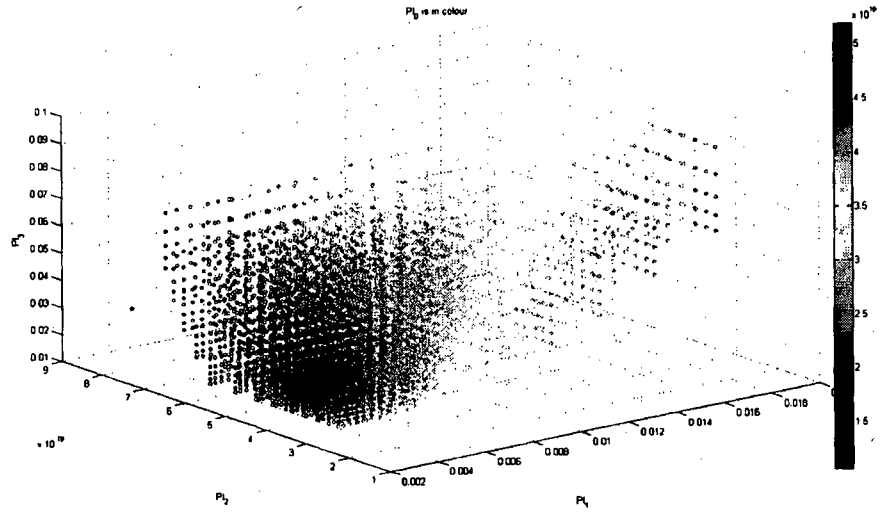


FIGURE 17B

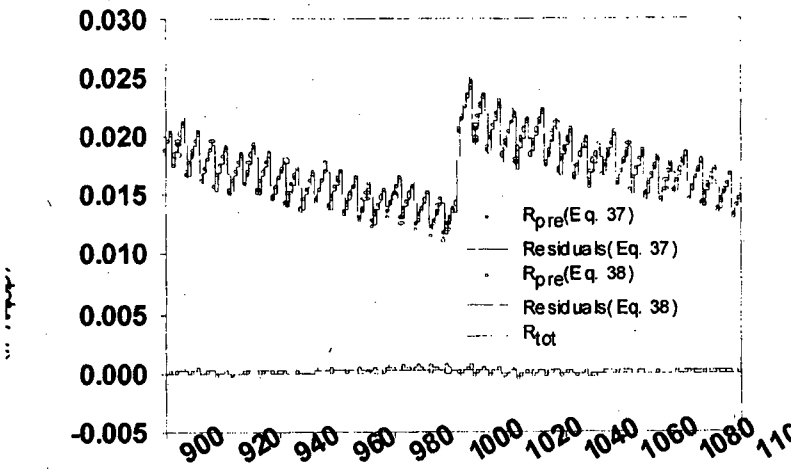


FIGURE 18

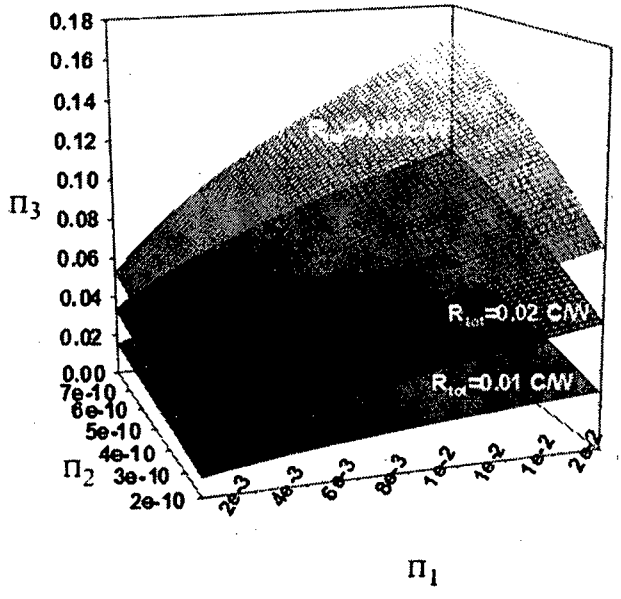


FIGURE 19A

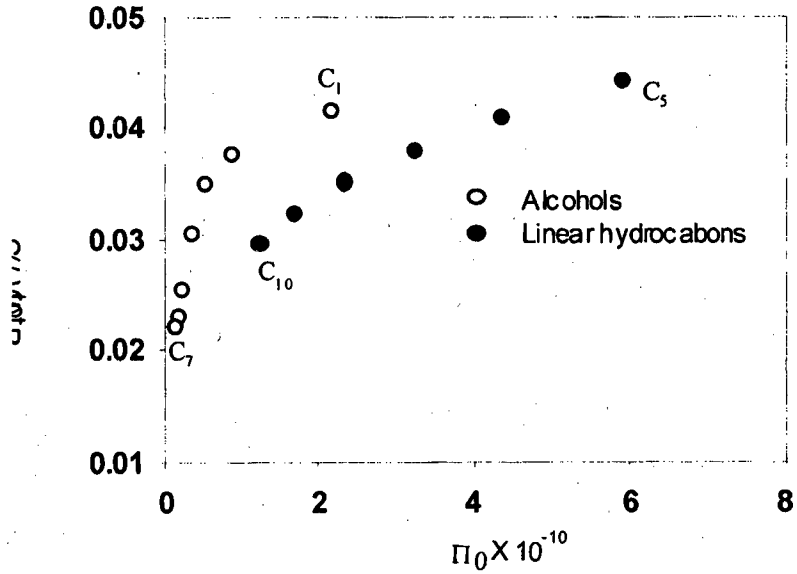

0.05
0.04
0.03
0.02
0.01
0
2
4
6
8
$\Pi_0 X 10^{-10}$
C_1
C_5
C_{10}
C_7
Alcohols
Linear hydrocabons

FIGURE 19B

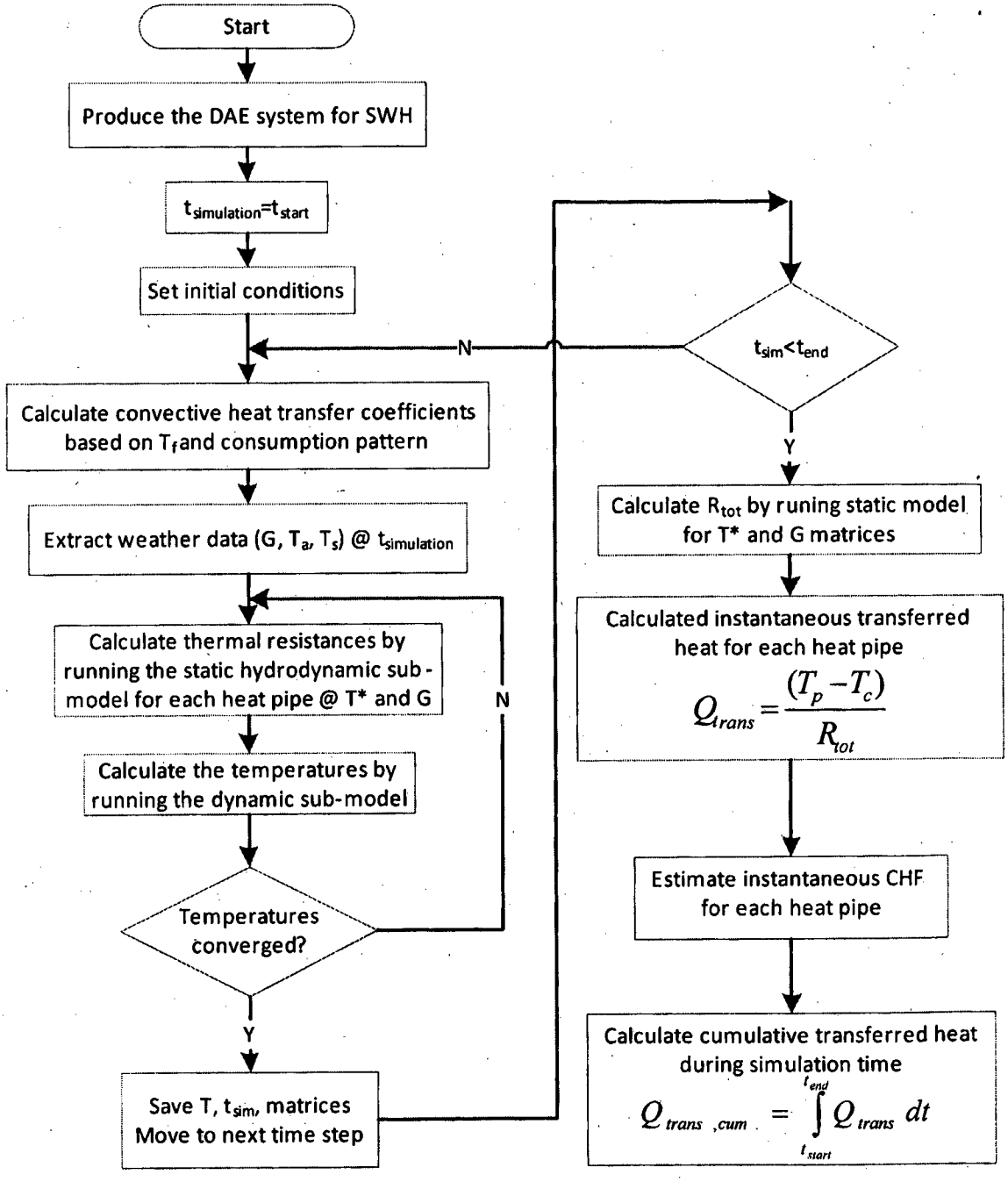

Start
Produce the DAE system for SWH
$t_{simulation}=t_{start}$
Set initial conditions
Calculate convective heat transfer coefficients based on T_f and consumption pattern
Extract weather data (G, T_a, T_s) @ $t_{simulation}$
Calculate thermal resistances by running the static hydrodynamic sub-model for each heat pipe @ T* and G
Calculate the temperatures by running the dynamic sub-model
Temperatures converged?
N
Y
Save T, t_{sim}, matrices
Move to next time step
N
$t_{sim}<t_{end}$
Y
Calculate R_{tot} by runing static model for T* and G matrices
Calculated instantaneous transferred heat for each heat pipe
$Q_{trans}=\frac{(T_p-T_c)}{R_{tot}}$
Estimate instantaneous CHF for each heat pipe
Calculate cumulative transferred heat during simulation time
$Q_{trans,cum}=\int_{t_{start}}^{t_{end}} Q_{trans}\,dt$

FIGURE 20

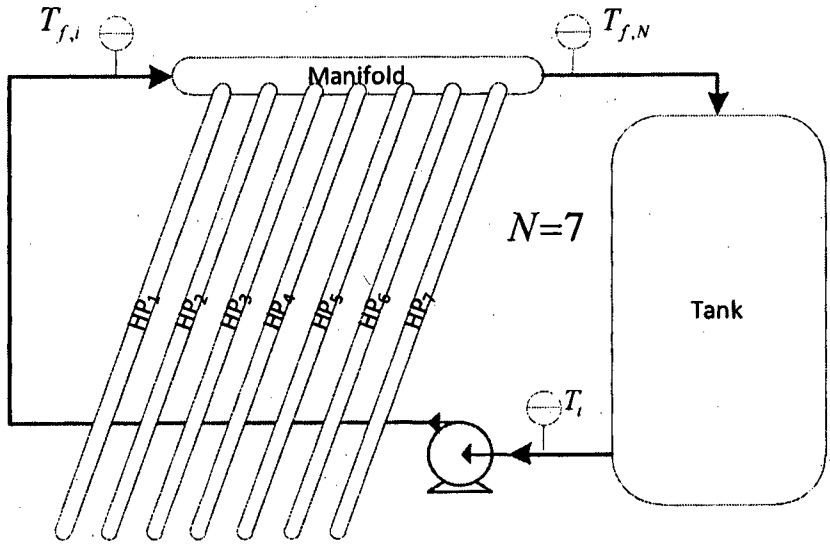


FIGURE 21

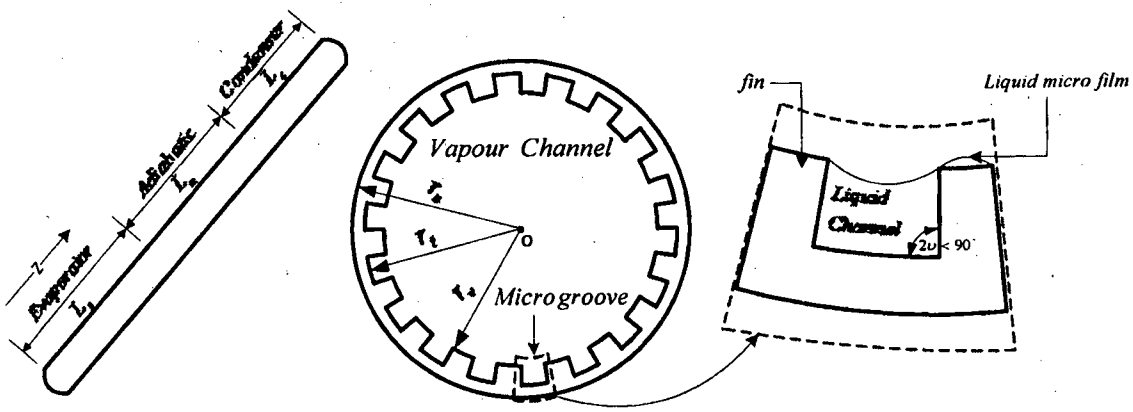


FIGURE 22

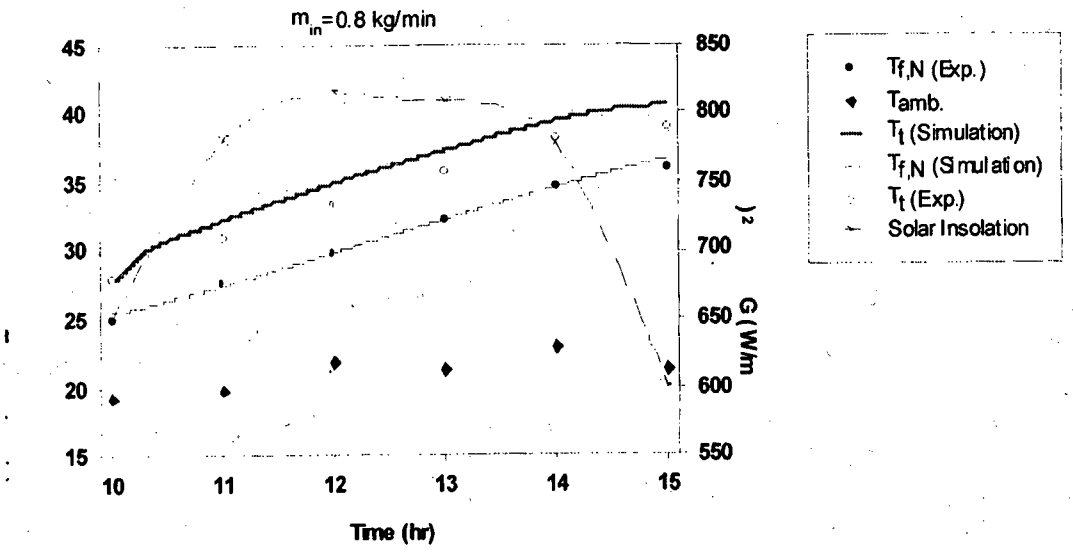


FIGURE 23A

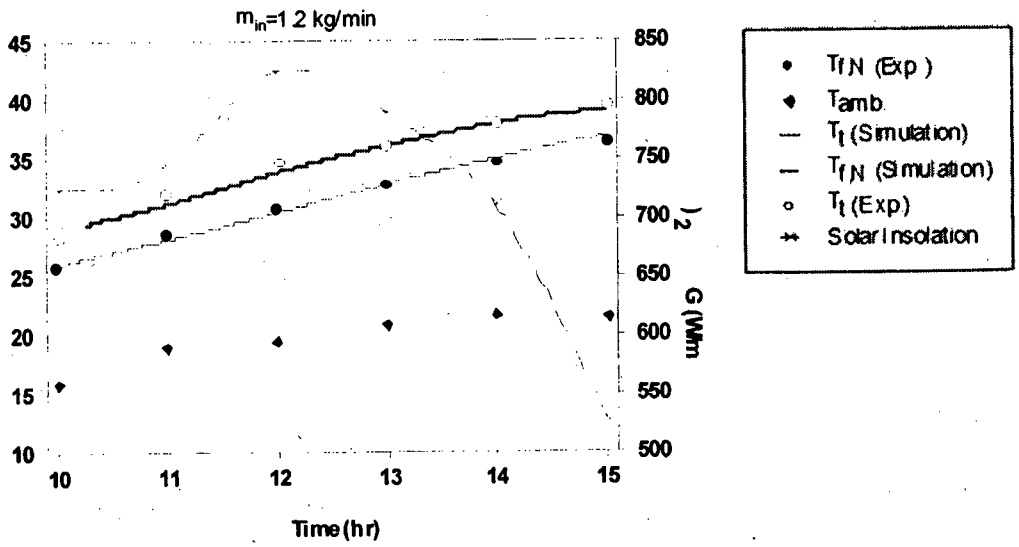


FIGURE 23B

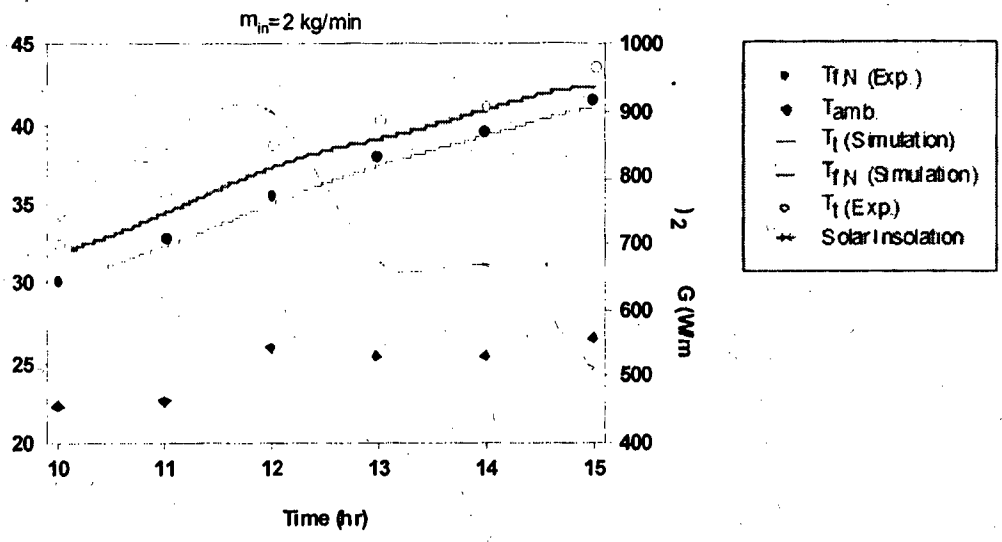


FIGURE 23C

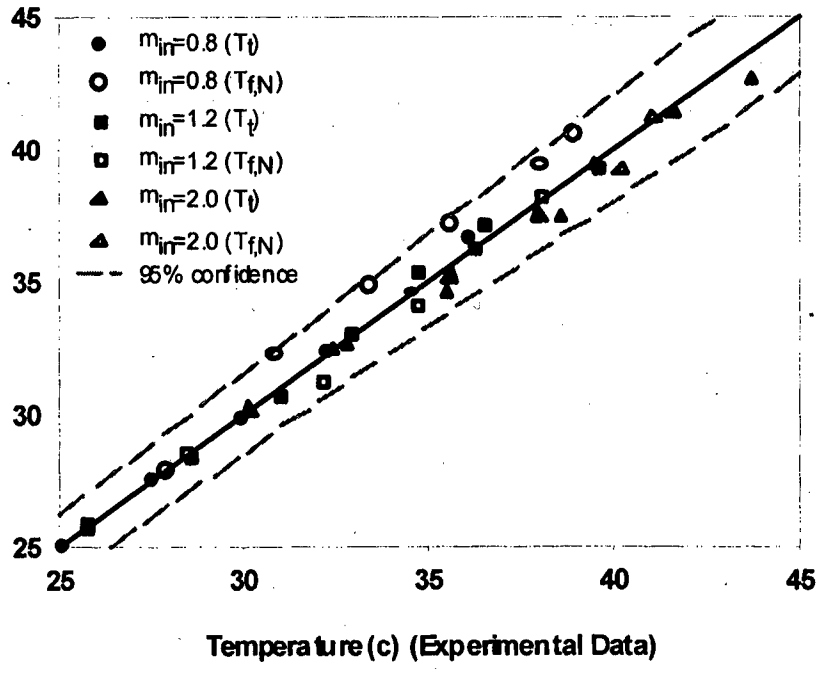


FIGURE 24

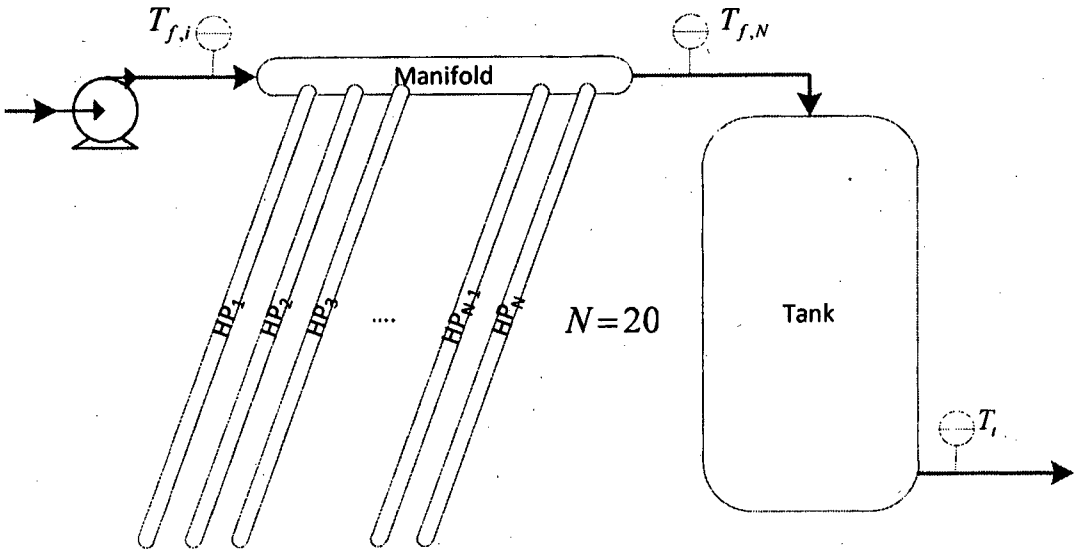


FIGURE 25

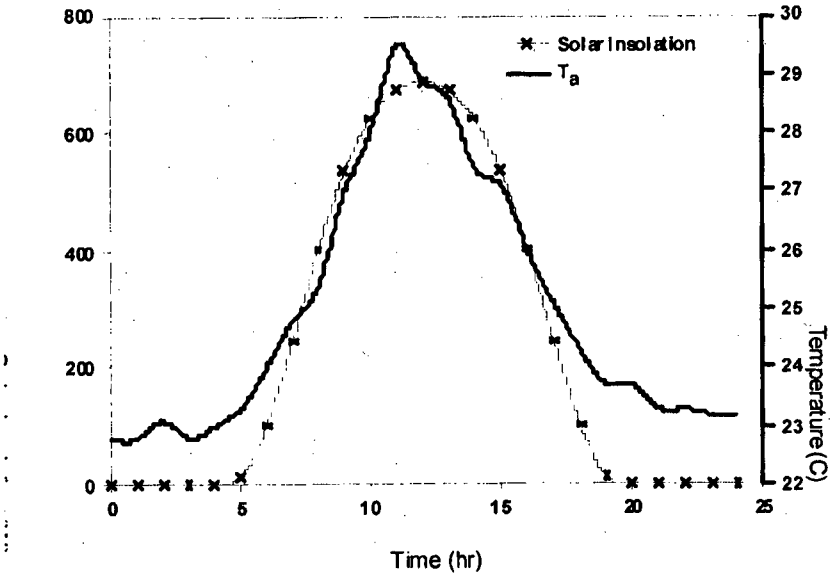


FIGURE 26

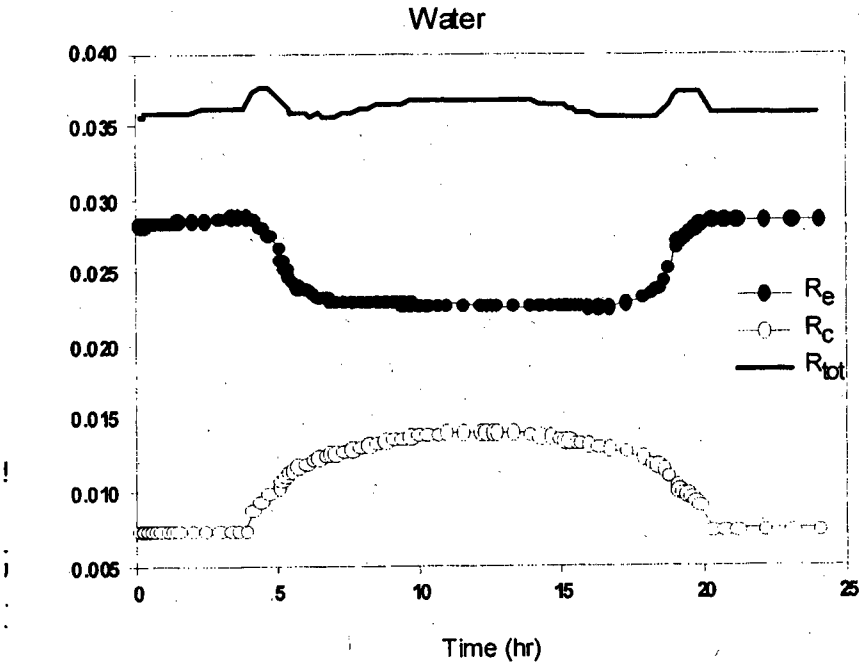


FIGURE 27

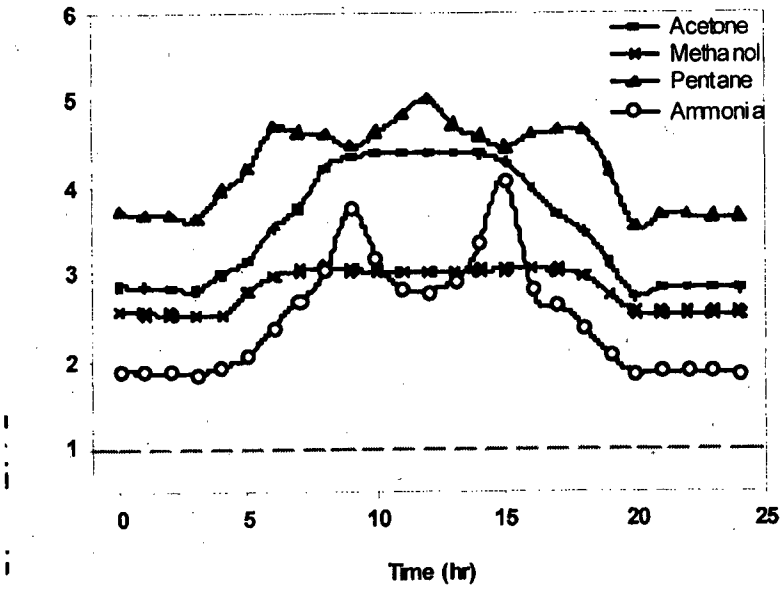


FIGURE 28

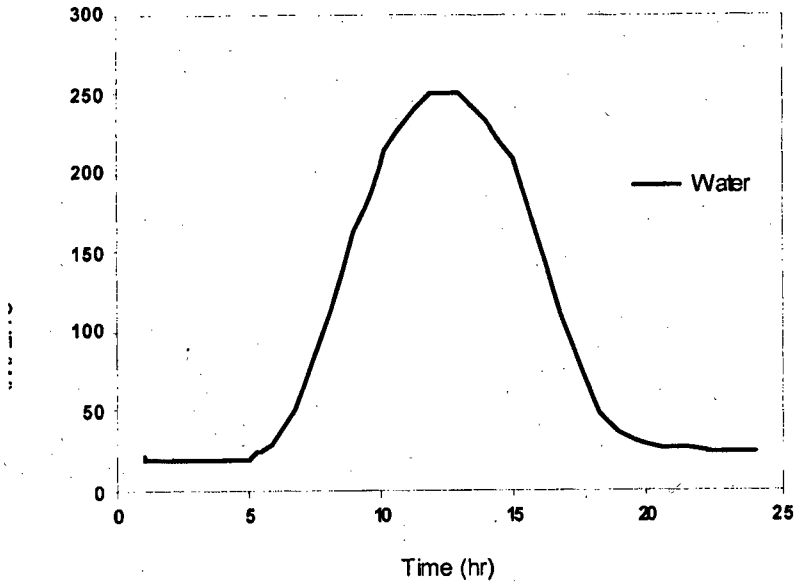


FIGURE 29

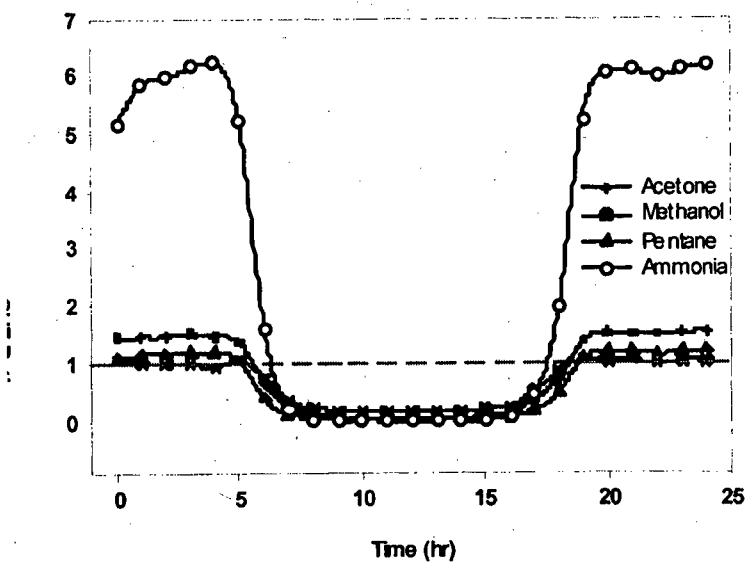


FIGURE 30

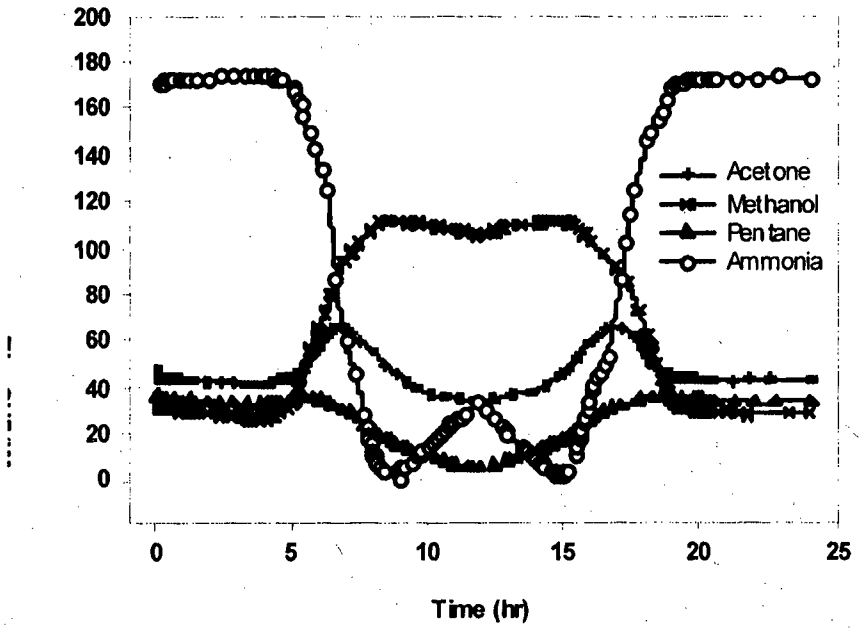


FIGURE 31

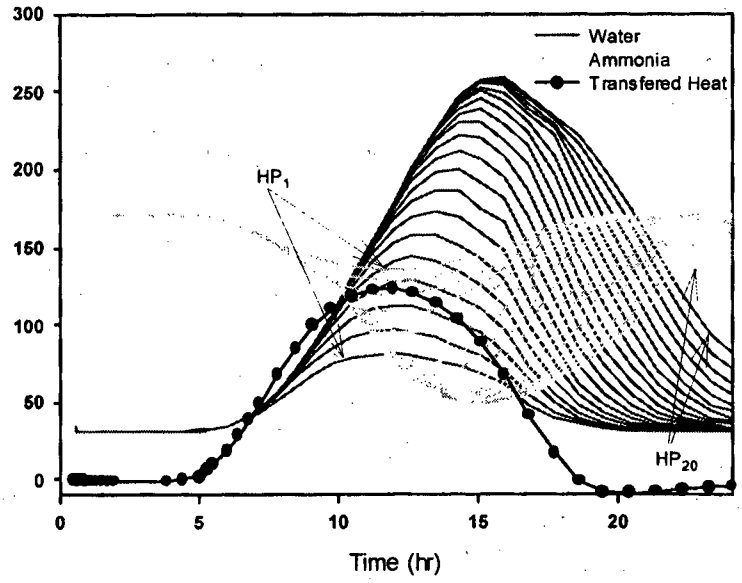


FIGURE 32

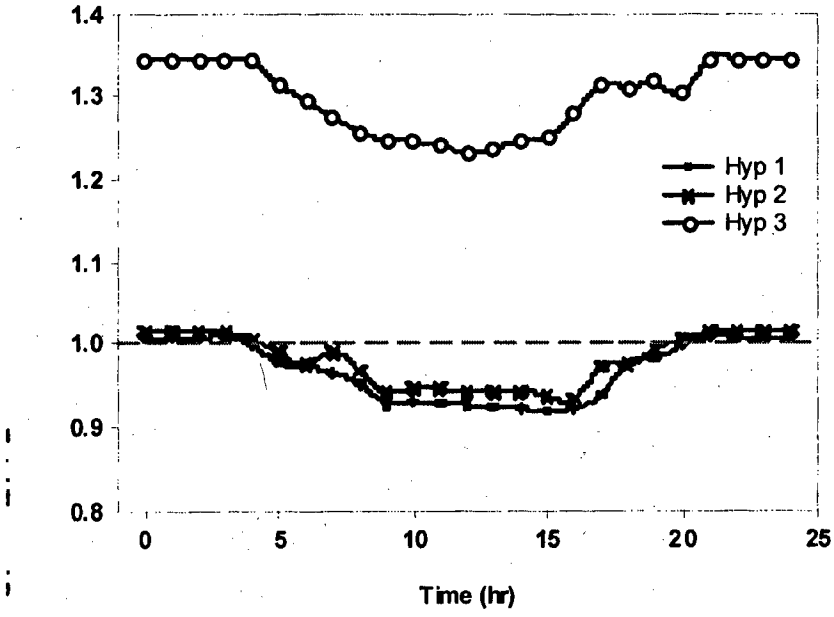


FIGURE 33

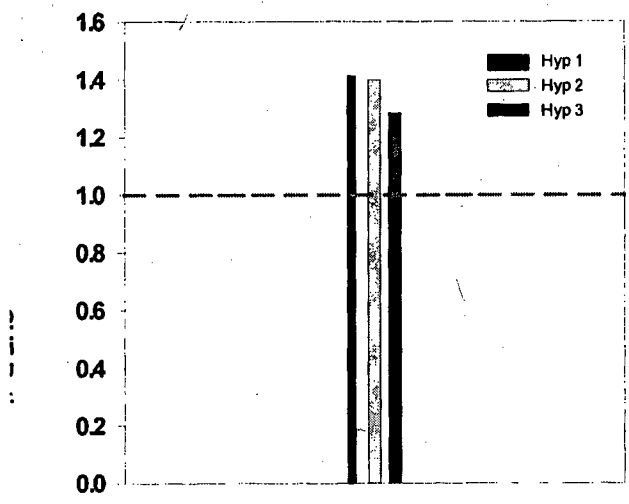


FIGURE 34

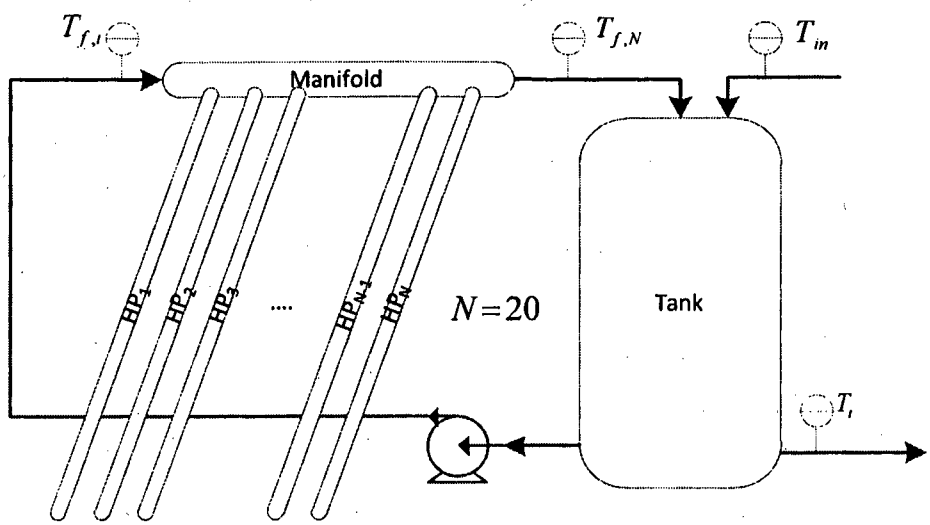


FIGURE 35

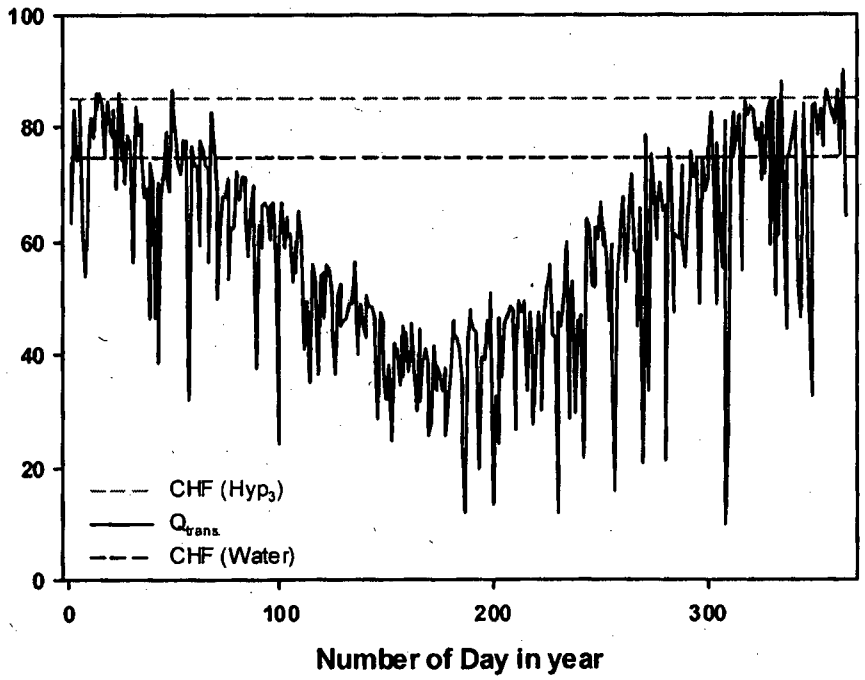


FIGURE 36

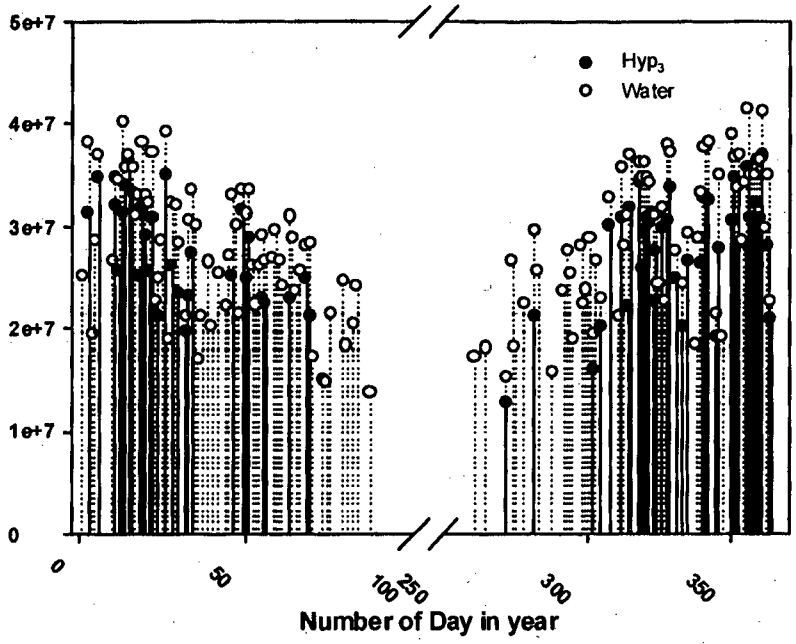


FIGURE 37

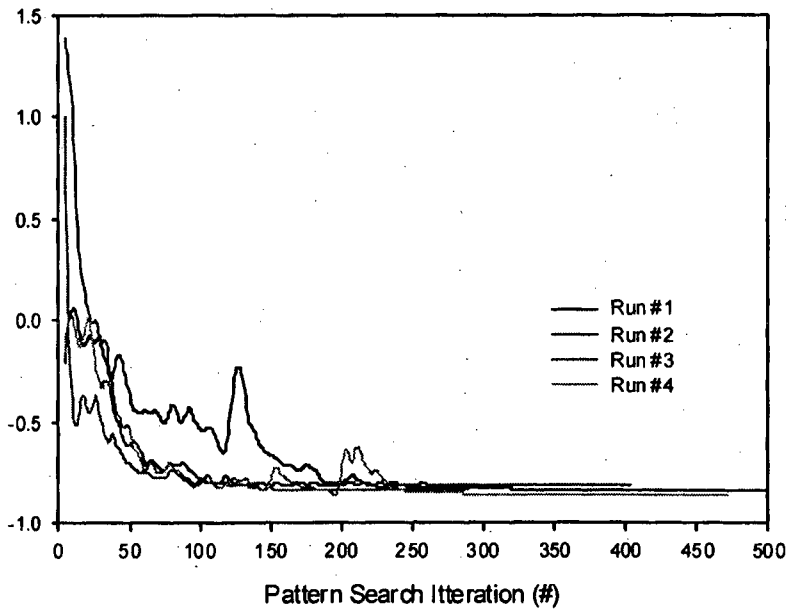


FIGURE 38

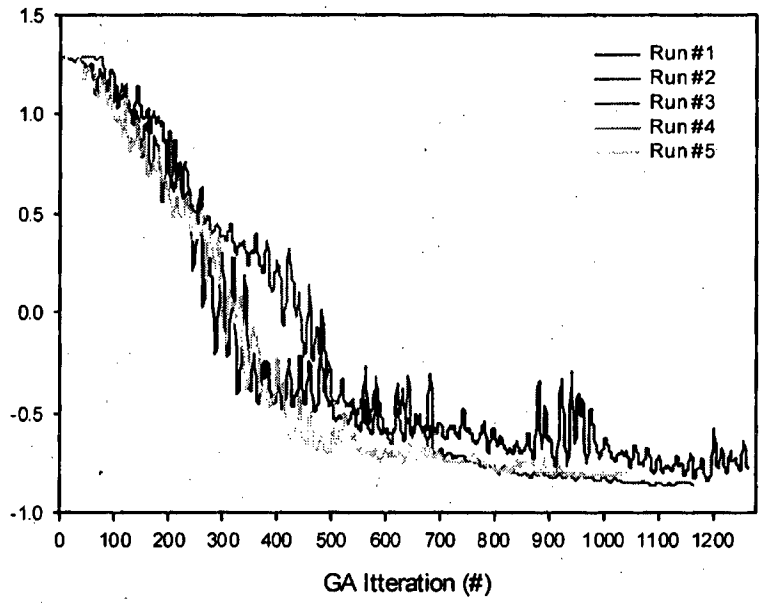


FIGURE 39

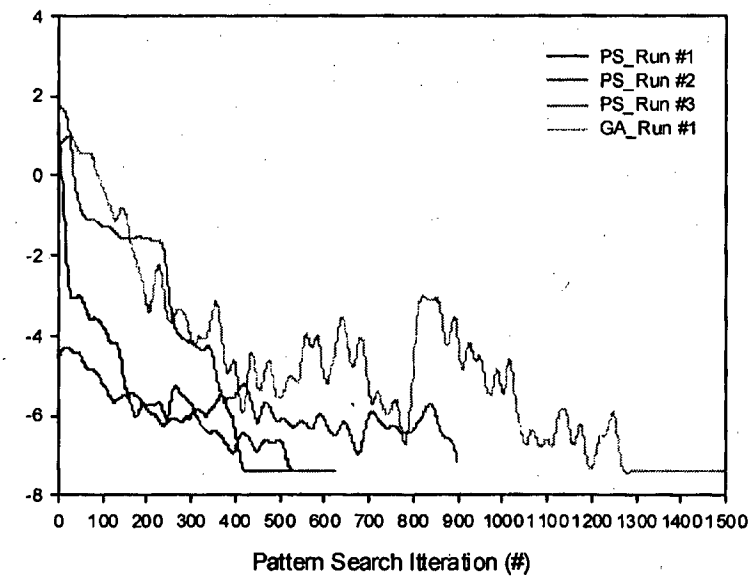


FIGURE 40

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2013/001254

A. CLASSIFICATION OF SUBJECT MATTER

G06F 17/50 (2006.01) G06N 3/12 (2006.01) C09K 5/00 (2006.01) F24J 2/05 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC: IPC G06N, G06F & Keywords (modelling, theoretical, algorithm, optimisation, working fluid, heat pipe, design, selection, plurality) & like terms; INSPEC: Keywords (modeling, theoretical, algorithm, working fluid, heat pipe, design, selection, optimisation) & like terms; Google Scholar: Keywords (optimal working fluid, mathematical model, heat transfer, parametric optimization, genetic algorithm, objective function) & like terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 February 2014	12 February 2014

Name and mailing address of the ISA/AU

AUSTRALIAN PATENT OFFICE
PO BOX 200, WODEN ACT 2606, AUSTRALIA
Email address: pct@ipaustralia.gov.au
Facsimile No.: +61 2 6283 7999

Authorised officer

Melanie O'Byrne
AUSTRALIAN PATENT OFFICE
(ISO 9001 Quality Certified Service)
Telephone No. 0262837974

INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. **PCT/AU2013/001254**
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Wang, Z. et al., 'Fluid selection and parametric optimization of organic Rankine cycle using low temperature waste heat', Energy, 14 March 2012, vol 40, pages 107–115 Abstract, Tables 1–3, Figures 3 & 7, pages 107–114	1–4, 7–42
P,X	Arab, M. et al., 'Model-based design and analysis of heat pipe working fluid for optimal performance in a concentric evacuated tube solar water heater', Solar Energy, August 2013, vol 94, pages 162–176 Whole document	1–42
T	Arab, M. et al., 'Optimization-Based Design and Selection of Working Fluids for Heat Transfer: Case Study in Heat Pipes', Ind & Eng Chem Res, 22 November 2013, vol 53, pages 920–929 Whole document	1–42

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2013/001254**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.