Jan. 9, 1968 J. A. OLSON 3,362,468

SURFACE CONDENSER

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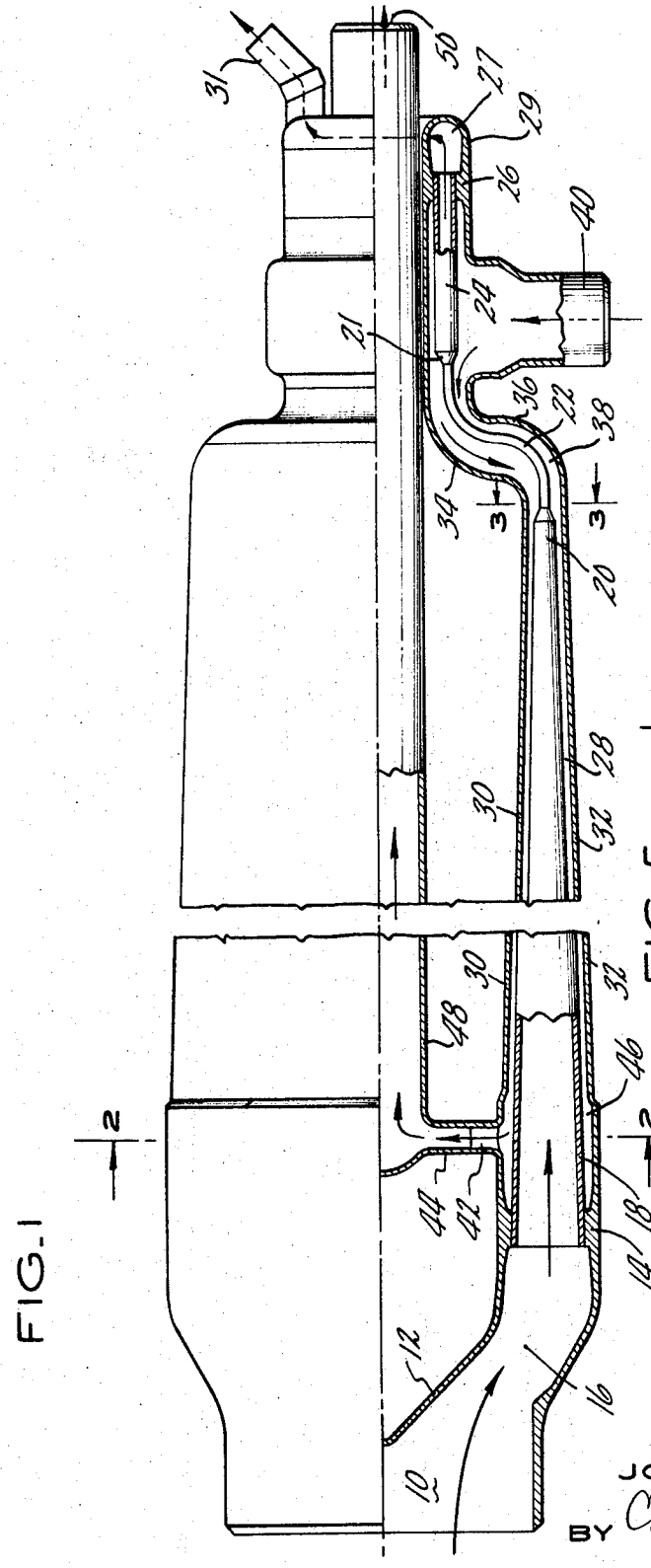


FIG. 1

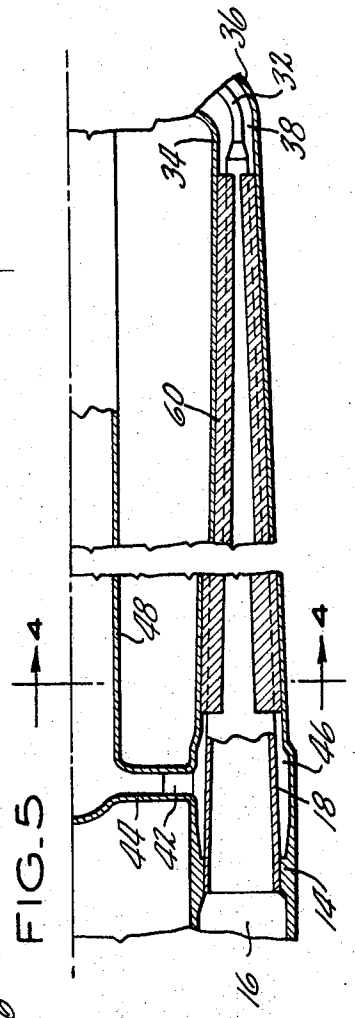


FIG. 5

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FIG. 2

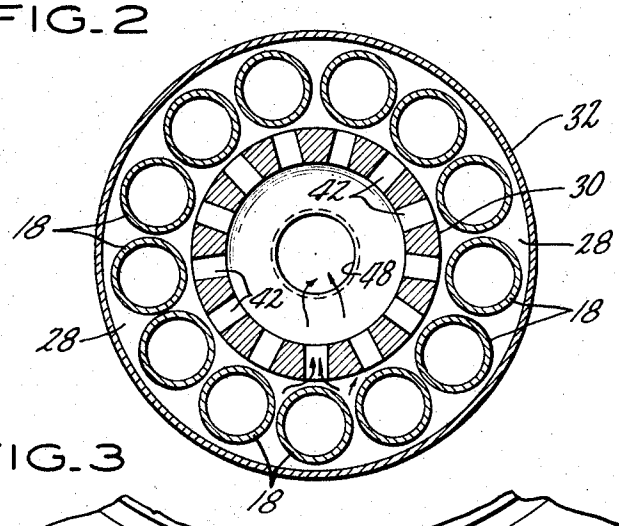


FIG. 3

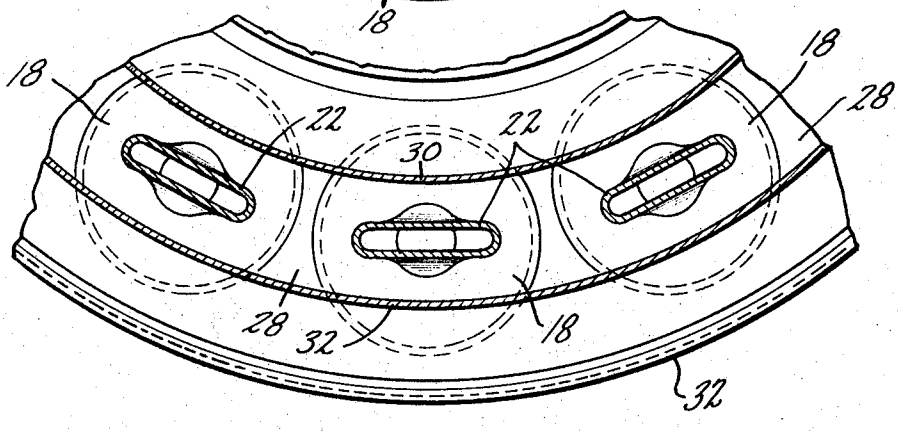
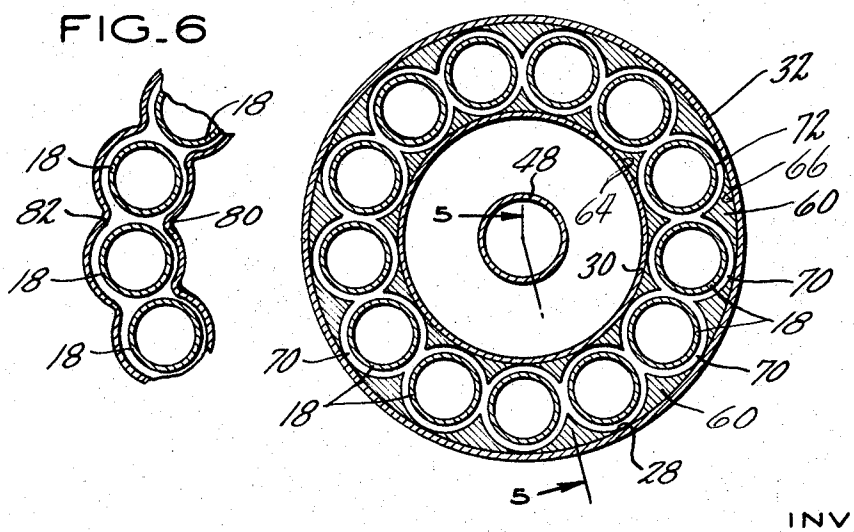


FIG. 4

FIG. 6



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SURFACE CONDENSER

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This invention relates generally to condensers and more particularly to surface condensers of the shell and tube type which are particuarly adapted to the condensation of high temperature liquid metal vapor in a zero gravity environment.

In recent years considerable effort has been directed toward the development of a closed-circuit, Rankine cycle, thermal powerplant for the long term generation of electrical power in outer space. In a typical powerplant of this type, a liquid metal, such as potassium, circulating in a closed cycle and vaporized by the addition of energy from a nuclear heat source, is conducted to and through a fluid turbine wherein energy is extracted in the form of useful work, the vapor subsequently being exhausted into a condenser. Additional energy is extracted in the condenser whereby the vapor is reduced to condensate and collected for subsequent return to the heat source. The condenser serves both to reduce the back pressure on the turbine, increasing its efficiency, and to conserve the fluid exhausted thereto from the turbine, thereby forming an integral part of the system.

In conventional condenser design, gravity is utilized to effect the liquid-vapor separation in the condensing process and in the subsequent collection of condensate to provide a vapor-free, positive suction head for the feed or booster pump. In the absence of gravity, other means must be provided to perform the functions heretofore performed by gravity. For this reason it has been necessary to depart somewhat from the traditional concepts of condenser design. In addition to the zero gravity problem, it is quite obvious that a space system condenser must be lightweight because of launching limitations, reliable because of its inaccessibility after launching, durable for maximum utility and economy, and relatively stable in operation. The problems are further magnified because the system parameters usually specified require operation at elevated temperatures with working fluids of a very corrosive nature.

It is an object of this invention to provide a condenser of the shell and tube type which is particularly adapted to the condensation of liquid metal vapor in a zero gravity environment.

A further object is to provide a condenser in which a stable liquid-vapor interface is maintained by forced convection forces and fluid surface tension in tapered tubes.

A still further object is to provide condensing apparatus wherein the fluid dynamics of the system are utilized in lieu of gravity to collect the condensate therefrom and provide a positive vapor-free suction head to the system feed pump.

Still another object is the provision of a lightweight and compact condenser wherein condensation takes place internal of a plurality of tapered tubes each of which incorporates an integral thermal expansion joint intermediate its ends.

A further feature is the provision of a condenser in which fluid hold-up is held to a minimum and which will operate in any orientation in a gravity field.

These and other objects and advantages will be obvious or will be specifically pointed out in connection with the following detailed description of several embodiments of the invention as shown in the accompanying drawings.

FIG. 1 is a longitudinal view of one embodiment of the invention shown in partial section;

FIG. 2 is a sectional view taken on line 2—2 of FIG. 1;

FIG. 3 is an enlarged sectional view taken on line 3—3 of FIG. 1;

FIG. 4 is a sectional view taken on line 4—4 of FIG. 5 illustrating optional flow-defining inserts surrounding each of the condenser tubes;

FIG. 5 is a longitudinal view of an embodiment of the invention shown in partial section illustrating the longitudinal position of the optional flow-defining inserts;

FIG. 6 is a fragmentary section of another embodiment of the invention illustrating the use of corrugated shells in lieu of the flow-defining inserts of FIGS. 4 and 5.

In the embodiment of the invention shown in FIGS. 1 and 2, the condenser is illustrated as generally of the shell and tube type in which condensation is effected internal of a plurality of tapered tubes arranged in an annular configuration. In the particular embodiment shown, the tubes are arranged in a single annular row. Vapor at high temperature, typically a turbine exhaust, is introduced to the condenser at vapor inlet **10**. The incoming vapor stream is divided by flow-splitter **12** and is directed by annular plenum chamber **16** to annular header **14**. A plurality of tapered tubes are welded or otherwise affixed to header **14** in a leak-tight manner and extend substantially parallel to the longitudinal axis of the condenser. The tubes **18** are tapered for a substantial portion of their length and thereby present a progressively decreasing cross-sectional flow area to the vapor in the direction of flow. Condensation of the vapor takes place internal of the tubes **18** and is effected entirely within the tapered length of the tubes. Therefore, condensation is complete at the points of minimum tapered tube diameter **20**.

As has been indicated, the tube **18** is formed with a taper over a substantial portion but not the entire tube length, a substantial portion being left untapered. A section of the untapered length, shown between locations **20** and **21** in FIGURE 1, is flattened (FIGURE 3) and bent relative to the tube axis to form a thermal expansion joint **22** which is integral with the tube itself. It is evident that the tube is preferably flattened in the direction of the bend for maximum flexibility and minimum stress in the tube wall during flexure. Although the expansion joint **22** is illustrated as bent radially inward to reduce the unit weight, it will be understood that, for the purposes of accommodation of the thermal expansion forces acting on the tube, the bend may be made in any direction relative to the tube axis. By providing a thermal expansion joint which is integral with the tube itself, all tube welds are eliminated and the reliability of the system is thereby enhanced.

Downstream of expansion joint **22** each tube is maintained in its normal tubular shape **24** for ease of fabrication, and is affixed at its extreme downstream end to a second annular header **26**. Condensate from tubes **18** is collected in chamber **27** formed between header **26** and annular closure member **29**, and is discharged from the condenser through exit pipe **31**.

A problem with compact condensers, where condensation is effected tube-side, is that of combining a reasonable size and number of tubes with reasonable vapor velocities at the tube inlets. In a straight untapered tube designed to discharge the high density fluid at a reasonable linear rate, the required mass flow of low density vapor will result in an excessive vapor inlet velocity from a fluid dynamic standpoint. Erosion under such conditions may be particularly severe. A tapered tube may therefore be utilized to great advantage. Using a tapered tube of progressively decreasing diameter, both the inlet vapor velocity and the exit liquid velocity may be established at their optimum levels. The use of the tapered tube further provides a substantial saving in material and weight.

However, if the tapered condenser tube is to be operated in a zero-gravity field, an additional problem is encountered. In the absence of gravity, the transition or interface from the vapor to the liquid state must be stabilized by a substitute force. There has been found to be a substantial correlation between the internal diameter of the tube and the stability of the liquid-vapor interface. If the tube diameter is too greater, it is not possible to maintain a stable interface without the assistance of gravity. For example, the milk bottle held inverted soon empties while the perfume bottle will remain full in the same circumstance. The maximum diameter at which the liquid retention phenomenon will occur is known as the critical diameter and its dimensions are dependent upon both the physical characteristics of the fluid itself, primarily its surface tension, and the characteristics of the system in which the fluid is contained.

The maximum diameter which will provide reasonable interfacial stability may be calculated from the following equation:

$$D=1.835\sqrt{\frac{s}{g(1-v)}}$$

where:

D=critical diameter
s=surface tension
g=acceleration due to gravity
l=liquid density
v=vapor density

In the condenser of this invention the force of surface tension is substituted for that of gravity to maintain the requisite stable interface. The surface tension force in the system is accordingly increased to the point where it controls and stabilizes the liquid-vapor interface by reducing the hydraulic diameter of the passage in the tapered portion of the tube and/or in the flattened portion of the tube below the critical diameter. It is, of course, quite obvious that as the diameter is reduced, the surface tension is increased correspondingly. In the condensing tubes of the condenser shown, the tube diameter is progressively decreased in the direction of vapor flow and the hydraulic diameter is further decreased by the flattening of the tubes downstream of the tapered portion. It may be seen, therefore, that the flattened portion of the tubes **18** beginning at location **22** serves a dual purpose, i.e., increased stabilization of the liquid-vapor interface due to an increase of surface tension forces in the flattened portion and convenient means for accommodating thermal expansion forces acting on the tube by bending of the flattened portion with respect to the tube axis.

Referring again to FIGS. 1 and 2, it may be seen that the tubes **18** extend longitudinally through an annular chamber **28** formed between an inner shell **30** of progressively increasing diameter and an outer shell **32** of progressively decreasing diameter, the two shells **30** and **32** being concentric and being tapered for substantially the same length as the tubes which they surround. The tapered shells **30** and **32** are affixed at one end to annular header **14** and at their other end to expansion-accommodating members **34** and **36** respectively. The expansion-accommodating members **34** and **36** have the same general configuration as that of tube expansion point **22** and, when welded to shells **30** and **32**, form an annular space **38** in which the expansion joint **22** may flex. The expansion-accommodating member **36** is in turn welded to plenum enclosure **38** which includes shell side fluid inlet **40**. Member **34** and enclosure **39** are welded to the inner and outer periphery, respectively, of header **26** forming annular chamber **28** in which the cooling fluid is confined.

The shell-side fluid, which may be a liquid metal such as a sodium-potassium alloy of low melting point, is introduced to the condenser at inlet **40** and flows generally parallel but counter to the vapor flow inside the condensing tubes **28**. The heated cooling fluid is discharged from annular chamber **28** through a plurality of ports **42** machined in transition member **44**. As may be most clearly seen in FIGURE 1, shell members **30** and **32** are preferably formed so that annular chamber **28** is slightly enlarged in the area of the discharge ports **42** to provide a plenum chamber **46** in which the shell-side fluid may flow with minimum pressure drop to ports **42**. Ports **42** communicate with longitudinal discharge pipe **48** through which the shell-side fluid is discharged from the condenser at **50**.

As may be mostly clearly seen in FIGS. 4 and 5, flow-defining inserts **60** may be provided in annular chamber **28** substantially surrounding and radially spaced from condensing tubes **18** and closely conforming to the outer and inner surfaces of the annular chamber **28** formed by tapered shells **30** and **32**, respectively. The inserts **60** extend longitudinally in annular chamber **28** between plenum chamber **46** and annular space **28**. Preferably, inserts **60** are solid or, if hollow, are leak-tight and are adapted to fit closely to the outer and inner walls of shells **30** and **32**, respectively, effectively blocking the passage of the shell-side fluid past surfaces **64** and **66**. The inserts are positioned in the annular chamber to form a plurality of apertures through which the tubes **18** pass and may be held in their circumferential and longitudinal positions by a series of tack welds joining the inserts with the internal surfaces of annular chamber **28**. With the inserts installed, a small annular space **70** is provided around each condensing tube **18**. The inserts thereby confine the cooling shell-side fluid to the immediate area surrounding the heated wall **72** of tube **18**, thereby enhancing the shell-side heat transfer characteristics of the condenser. Because of the presence of inserts **60**, the shell-side fluid inventory of the condenser is reduced, resulting in a substantial decrease in system weight.

It is, of course, quite obvious that when fabrication costs outweight weight considerations, shells **30** and **32** may be fabricated without a taper. In this case, the outer surface of the inserts would not be tapered longitudinally, but would be adapted to closely conform to the straight cylindrical walls of the annular chamber into which they fit.

FIGURE 6 is a fragmentary view depicting another embodiment of this invention. In this embodiment tapered corrugated shells **80** and **82**, corresponding to shells **30** and **32**, respectively, of the embodiment shown in FIGURE 4, are circumferentially oriented with respect to each other so as to form therebetween a plurality of tube-receiving apertures. The corrugated shells are thus employed in lieu of the flow-defining inserts **60** of FIG. 4 to channel the flow of the shell-side fluid and reduce the liquid metal inventory in the condenser.

It will be evident that as a result of the constructional features of this invention a surface condenser has been provided which is particularly adapted to the high temperature condensation of vapor in a zero-gravity environment. By judicious design, the forces of surface tension have been employed to provide a stable liquid-vapor interface in the condensing process, thereby compensating for the absence of gravity in a space embodiment, and incidentally providing a condenser which is operable in any orientation in a gravity field.

It will also be evident that a condenser has been provided which is compact and lightweight and in which the liquid metal inventory therein is minimized. Through the use of tapered shells and tapered tubes, a substantial saving in materials is achieved resulting in an overall decrease in the dry weight of the condensing unit.

While the apparatus shown and described herein represent preferred embodiments of the invention, it will be understood that numerous changes may be made in the construction and arrangement of the parts without exceeding the scope of the invention as defined by the following claims.

I claim:

1. A condenser comprising an outer tapered shell of progressively decreasing diameter, an inner tapered shell of progressively increasing diameter concentric with said outer shell, the taper angle of each of said shells being substantially equal, a first annular header joining said shells at one end, a second annular header joining said shells at their other end forming therebetween an annular tapered chamber, a plurality of tapered tubes of progressively decreasing diameter communicating with each header and having the maximum diameter adjacent the inlet header and extending longitudinally through said annular chamber, means to maintain a stable vapor-liquid interface comprising the minimum diameter of each of said tubes being less than the critical diameter for the fluid being condensed, the taper of said tubes substantially conforming to the taper of said annular chamber, an inlet and outlet to said annular chamber, and an annular inlet affixed to said first header and an annular outlet affixed to said second header for confining the tube side fluid.

2. The condenser of claim 1 in which the tapered tubes are equally spaced in each of said headers in a single annular row.

3. In a liquid metal heat exchanger, an outer tapered corrugated cylindrical shell, an inner tapered corrugated cylindrical shell concentric therewith, said shells being circumferentially oriented with respect to each other to form a plurality of tube-receiving apertures therebetween, a first annnular header joining said cylindrical shells at one end, a second annular header joining said cylindrical shells at their other end forming therebetween an annular tapered chamber, a plurality of tapered tubes communicating with each header and having the maximum diameter adjacent the inlet header and extending longitudinally through said annular chamber in said tube-receiving apertures, means to maintain a stable vapor-liquid interface comprising the minimum diameter of each of said tubes being less than the critical diameter for the fluid being condensed, and an inlet and outlet to said chamber for circulating fluid therethrough.

4. In a liquid metal condenser, inner and outer cylindrical shells, a first header joining said shells at one end, a second header joining said shells at their other end forming therebetween an annular chamber, a plurality of tapered tubes in said annular chamber extending between each of said headers and communicating with each header and having the maximum diameter adjacent the inlet header, each tube having a flattened portion of substantial length intermediate the ends thereof, said flattened portion being bent relative to the tube axis to effect an expansion joint, means to maintain a stable vapor-liquid interface comprising the hydraulic diameter of the flattened portion of said tapered tubes being less than the critical diameter for the fluid being condensed, and an inlet and outlet to said annular chamber for circulating shell-side fluid therethrough.

5. In a shell and tube condenser having an external shell connected between first and second tube headers to define a chamber for the shell-side fluid, a plurality of tapered tubes extending longitudinally through said chamber and communicating with each header and having the maximum diameter adjacent the inlet header, means to maintain a stable vapor-liquid interface comprising the minimum diameter of each of said tubes being less than the critical diameter for the fluid being condensed, and an inlet and outlet to said chamber for circulating the shell-side fluid therethrough.

6. A condenser comprising an outer cylindrical shell, an inner cylindrical shell concentric therewith and radially spaced therefrom, a first header joining said shells at one end, a second header joining said shells at their other end, forming therebetween an annular chamber, a plurality of tubes tapered for at least a substantial portion of their length extending longitudinally through said chamber and communicating with each header and having the maximum diameter adjacent the inlet header, means to maintain a stable vapor-liquid interface comprising the minimum diameter of each of said tubes being less than the critical diameter for the fluid being condensed, and an inlet and outlet to said chamber for circulating a shell-side fluid therethrough.

7. The condenser of claim 6 which includes means for accommodating the differential thermal expansion between said tubes and said shell.

8. The condenser of claim 7 which includes a discharge conduit concentric with said shells and internal thereof extending through said second header to receive the shell-side fluid discharged from the annular chamber through the outlet.

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