HEAT PIPE - HIGH PERFORMANCE TECHNOLOGY IN HEAT TRANSFER

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Abstract: *The basic heat pipe consists of a vacuum chamber from which all non-condensable gases have been discharged and which contains a capillary structure and a certain amount of two-phase fluid. However, a more general definition can be given, as the concept has since become much more comprehensive. Thus, the thermal tube is a device that achieves an efficient heat transfer by combining in a closed cycle the phenomena of vaporization, vapor transport, condensation and condensation return, of a working fluid. At first glance, the operation of the heat pipe seems to be extremely simple. The thermal energy is transported from the evaporator to the condenser through a continuous cycle of mass transfer and phase change of a working fluid.*
Keywords: *heat pipe, capillarity limit, sonic limit, flow boiling.*

1. INTRODUCTION

The basic thermal tube, as patented, consists of a vacuum chamber from which all non-condensable gases have been discharged and which contains a capillary structure and a certain amount of two-phase fluid.
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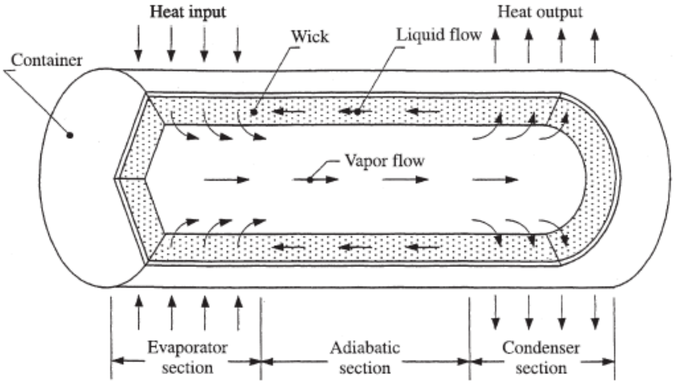

Figure 1 The main regions of the heat pipe

Figure 1 illustrates the operating principle of a cylindrical thermal tube. The working fluid in liquid state is vaporized in the evaporation zone where the thermal tube is in thermal contact with the hot source. The vapors flow to the condensation zone, where the heat tube is in thermal contact with the cold source, producing condensation of vapors by giving up the heat of vaporization. The condensate (liquid) in the condensation zone is returned to the evaporation zone by a maintained pumping mechanism.
For applications in the cosmic space, the pumping action is performed by the capillary forces that are created in a component of the thermal tube called capillary structure. It can be constructed from a porous material, from grooves incised in the material of the thermal tube shell, or from a complex structure using a combination of these processes.
In the case of terrestrial applications, gravitational mass forces are a very simple and effective means of returning condensation to the evaporation zone, the devices being improperly called by some author's two-phase

gravitational thermosiphons. These two means of achieving a maintenance pumping mechanism are the most used.
Thermal tubes are classified into two general types: conventional thermal tubes and variable conductance thermal tubes.
The conventional thermal tube is a device with a very high but relatively constant conductance, which does not have a constant operating temperature. Its temperature increases or decreases according to the variations of the hot or cold source. Many applications of the heat pipe have required adjusting the operating temperature of the heat pipe or one of the heat sources. These could only be obtained by varying the conductance of the thermal tube (the inverse of the thermal resistance).
The operating ranges of the thermal tubes are conventionally considered to be the following:

* cryogenic: 0 ... 150K, (-273 ...- 123°C);
* low temperatures: 150 ... 353K, (-123 ... 80°C);
* average temperatures: 353 ... 750K, (80 ... 477°C);
* High temperatures: 750 ... 3000K, (477 ... 2727°C).

Working fluids are generally chemical elements that in the normal physical state are gases for the field of cryogenic thermal tubes, polar molecules or organic substances in the field of low and medium temperature thermal tubes and liquid metals in the field of high temperature thermal tubes.
The fundamental properties of the thermal tube are:

* quasi-isothermal operation (its temperature is approximately constant);
* very high conductance;
* unitary heat flux transformer device: it can be designed so that the heat is absorbed by a small surface (thus with a very high thermal flux density) and evacuated by an extended surface with fins (so with a density very low thermal flux);
* can be designed as a device with variable conductance, its temperature being self-regulated or externally regulated.

Thermal tubes are used in many areas. Since the first International Conference on thermal tube, it has been appreciated that the technological implications of the device will be revolutionary, and the years that have passed have confirmed this forecast.
Conventionally, depending on the property used, the thermal tube can be designed as:

• efficient heat transfer device (recuperative heat exchangers - especially in the gas-gas system);
• device for iso-thermalizing some technological workspaces (isothermal furnaces for more demanding technological processes, calibration of temperature measuring devices, etc.);
• unitary transformer of thermal flux (cooling of electronic devices - diodes and thyristors, electronic computer, etc.);
• device for regulating the temperature (catalytic reactors, furnaces for semiconductor devices);
• unidirectional heat transfer device (thermal diode).

According to the technical fields in which it is used, the applications of the thermal tube are:

• Cooling: electronic devices, electric motors, thermo-ion generator manifold, electrical components, molds, radioactive sources, nuclear reactors, turbine blades, aircraft attack board, cutting tools, fuel cells, engines, freezing tundra soil under construction;
* heating: chemical reactors, coal gasification, defrosting of bridges and highways, isothermal furnaces, heating of oil at start-up of vehicles in winter, thermionic generator emitter, household applications etc;
* space technologies: temperature regulation, isothermal structures, cooling electronic devices, etc;
* Specialized uses: cryogenic scalpel, heat exchangers, emissivity measurement, surface tension, thermal conductivity, vaporization pressure, etc.

It should be noted that applications are not limited to the above areas and their approach is according to the imagination of the designer.

2. HEAT TRANSFER LIMITATIONS

In the operation of the heat pipes there are various parameters that impose limitations and restrictions on stationary or non-stationary operation [1] [2]. In other words, the rate of heat transfer through a heat pipe is restricted due to operating limits. Physical phenomena that could limit the heat transport in the thermal tubes are caused by capillary, sonic, entrainment, boiling, cold starting, vapor pressure and condensation effects.
The limitation of the heat transfer can be achieved by any of the above limitations, depending on the size and shape of the tube, the working fluid, the capillary structure and the operating temperature. The lowest operating limit of the eight constraints defines the maximum heat transfer limit of a heat pipe at a given operating temperature. The physical phenomena for each boundary are summarized below. A detailed presentation of the criteria for heat transfer limitations for thermal tubes is presented in [2] [4].

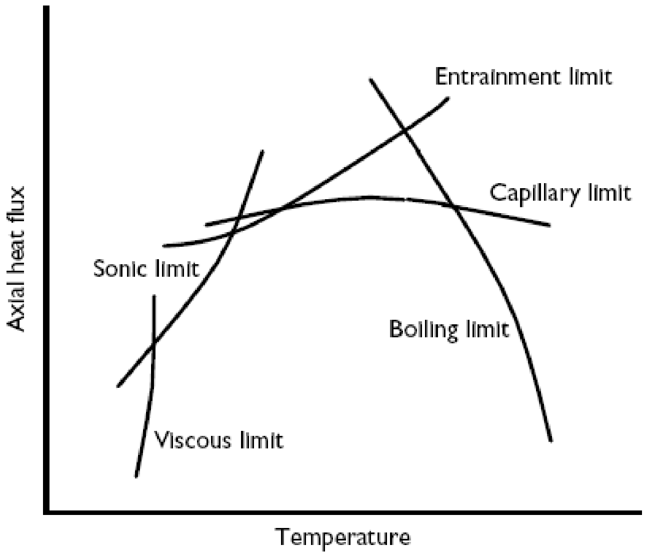

Figure 2 Limitations to heat transport in a heat pipe

2.1. Capillary Limit

The ability of a capillary structure to ensure the circulation of a given working fluid is limited [3] [2]. This limit is commonly referred to as capillary limit or hydrodynamic limitation. The capillary limit is the most commonly encountered limitation in the operation of thermal tubes at low operating temperatures. That occurs when pumping speed is not sufficient to provide enough liquid in the evaporation zone. This is because the sum of the pressure drops of the liquid and the vapor exceeds the maximum capillary pressure that the capillary structure can provide. The maximum capillary pressure for a given capillary structure depends on the thermophysical properties of the structure and the working fluid. The tendency to increase the heat transfer over the capillary boundary will cause drying in the vaporizer area, where there is a sudden increase in wall temperature along the boiling zone. This limit is commonly referred to as capillary limitation or hydrodynamic limitation.

2.2. Sonic Limit

The evaporator and condenser sections of a heat pipe represent a vapor flow channel with mass input and extraction due to evaporation and condensation respectively. The vapor velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. The limitation of such a flow system is similar to that of a convergent-divergent double nozzle with a constant mass flow rate. So, it is expected that the vapor velocity at that time will not exceed the local speed of sound. This state of blocked flow is called sonic limitation. The sonic limit usually occurs either during the start of the heat pipe or during the steady state operation when the heat transfer coefficient to the capacitor is high. The sonic limit is usually associated with liquid-metal heat pipes due to high vapor velocity and low densities. Unlike the capillary limit, when the sonic limit is exceeded, this is not a serious phenomenon. The sonic limitation corresponds to a given temperature at the end of the evaporator. Increasing the temperature of the final vaporizer cap will increase this limit to a new higher sonic limit. The intensity of the heat transfer will not increase by decreasing the capacitor temperature under choking conditions. Therefore, when the sonic limit is reached, the further increase of the heat transfer rate can be achieved only when the evaporator temperature rises. The operation of heat pipes with a near heat rate or sonic limit results in a significant decrease of the axial temperature along the heat pipe.

2.3. Boiling Limit

If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator wick boils and the wall temperature becomes excessively high. The vapor bubbles that form in the wick prevent the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dryout. It should be noted that the boiling limitation is a radial heat flux limitation as compared to an axial heat flux limitation for the other heat pipe limits. However, since they are related through the evaporator surface area, the maximum radial heat flux limitation also specifies the maximum axial heat transport. The boiling limit is often associated with heat pipes of non-metallic working fluids.

2.4. Entrainment Limit

A shear force exists at the liquid-vapor interface since the vapor and liquid move in opposite directions. At high relative velocities, droplets of liquid can be torn from the wick surface and entrained into the vapor flowing toward the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes with small diameters, or high temperature heat pipes when the heat input at the evaporator is high.

2.5. Vapor Pressure Limit

At low operating temperatures, viscous forces may be dominant for the vapor moving flow down the heat pipe. For a long liquid-metal heat pipe, the vapor pressure at the condenser end may reduce to zero. The heat transport of the heat pipe may be limited under this condition. The vapor pressure limit (or viscous limit) is encountered when a heat pipe operates at temperatures below its normal operating range, such as during startup from the frozen state. In this case, the vapor pressure is very small, with the condenser end cap pressure nearly zero.

2.6. Frozen Startup Limit

During the startup process from the frozen state, the active length of the heat pipe is less than the total length, and the distance the liquid has to travel in the wick is less than that required for steady state operations. Therefore, the capillary limit will usually not occur during the startup process if the heat input is not very high and is not applied too abruptly. However, for heat pipes with an initially frozen working fluid, if the melting temperature of the working fluid and the heat capacities of the heat pipe container and wick are high, and the latent heat of evaporation and cross-sectional area of the wick are small, a frozen startup limit may occur due to the freezing out of vapor from the evaporation zone to the adiabatic or condensation zone.

2.7. Condensing Heat Transfer Limit

In general, heat pipe condensers and the method of cooling the condenser should be designed such that the maximum heat rate capable of being transported by the heat pipe can be removed. However, in exceptional cases with high temperature heat pipes, appropriate condensers cannot be developed to remove the maximum heat capability of the heat pipe. Due to the presence of non-condensable gases, the effective length of the heat pipe is reduced during continuous operation. Therefore, the condenser is not used to its full capacity. In both cases, the heat transfer limitation can be due to the condenser limit.

2.8. Vapor Continuity Limit

For heat pipes with very low operating temperatures, especially when the dimension of the heat pipe is very small such as micro heat pipes, the vapor flow in the heat pipe may be in the free molecular or rarefied condition. The heat transport capability under this condition is limited, and is called the vapor continuum limit.

2.9. Flooding Limit

The flooding limit is the most common concern for long heat pipes with large liquid fill ratios, large axial heat fluxes, and small radial heat fluxes [4]. This limit occurs due to the instability of the liquid film generated by a high value of interfacial shear, which is a result of the large vapor velocities induced by high axial heat fluxes. The vapor shear hold-up prevents the condensate from returning to the evaporator and leads to a flooding condition in the condenser section. This causes a partial dryout of the evaporator, which results in wall temperature excursions or in limiting the operation of the system.

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