APPLICATION OF HEAT PIPES IN NUCLEAR REACTORS FOR PASSIVE HEAT REMOVAL

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ABSTRACT – This paper introduces a number of potential heat pipe applications in passive (i.e., not requiring external power) nuclear reactor heat removal. Heat pipes are particularly suitable for small reactors as the demand for heat removal is significantly less than commercial nuclear power plants, and passive and reliable heat removal is required. The use of heat pipes has been proposed in many small reactor designs for passive heat removal from the reactor core. This paper presents the application of heat pipes in AECL's Nuclear Battery design, a small reactor concept developed by AECL. Other potential applications of heat pipes include transferring excess heat from containment to the atmosphere by integrating low-temperature heat pipes into the containment building (to ensure long-term cooling following a station blackout), and passively cooling spent fuel bays.

1. Introduction and Principles of Heat Pipe Operation

A heat pipe is a heat-transport device that transfers heat from a heat source to a heat sink in an efficient manner using evaporation and condensation of a working fluid in a closed system. Heat pipes require no external power to operate, are highly reliable, and can transfer heat with efficiency several orders of magnitude greater than pure conduction through a solid metal [1]. A conventional heat pipe is composed of a sealed container, typically a pipe with end caps, a wick structure and a working fluid. A heat pipe has three regions along its length: an evaporator, an adiabatic section and a condenser. Figure 1 shows schematics of a conventional heat pipe (left), and a gravity assisted heat pipe (right).

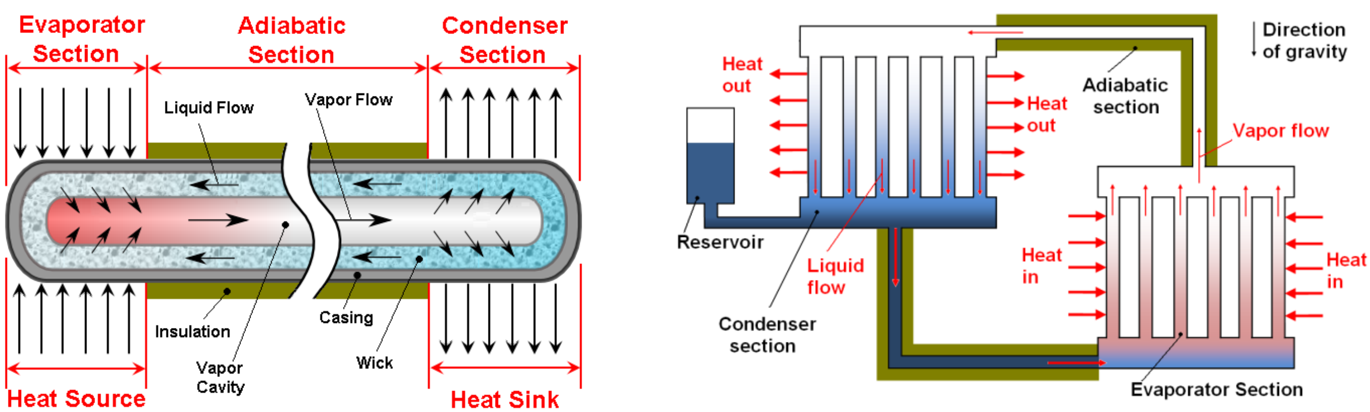

Figure 1 Schematic of a Conventional Heat Pipe (left) (adapted from [1]), and a Gravity Assisted Loop Heat Pipe (right)

Energy absorbed from the heat source by the evaporator causes the working fluid to evaporate. The expanding vapour flows from the evaporator to the condenser due to the difference in pressure. Heat is then rejected to the heat sink in the condenser as the vapour is condensed back to liquid, which then flows through a wick due to capillary action and returns to the evaporator where the cycle is repeated [1]. For applications involving transfer of large heat loads over long distances, thermal performance degrades due to increased pressure losses in the wick. For such applications, gravity-assisted loop heat pipes (see Figure 1), where the returning liquid flow uses gravity instead of the capillary action of a wicking material, are more appropriate.

2. Heat Pipe Application in the Nuclear Battery

The Nuclear Battery is a small, solid state, passively cooled nuclear power reactor concept developed by AECL from 1984 to 1989 for small-scale base load electricity generation at locations that are remote from utility grids and natural gas pipelines. One of the key technical features of the Nuclear Battery reactor core is a heat-pipe based primary heat transport system. Figure 2 shows a schematic of the Nuclear Battery reactor core.

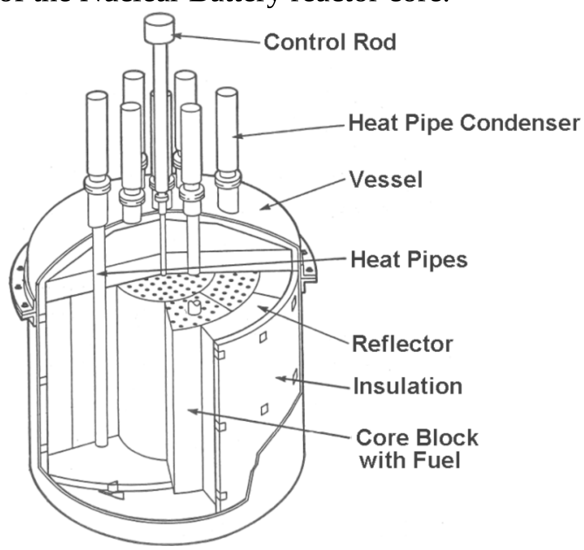

Figure 2 Nuclear Battery Reactor Core Module

Heat is passively removed from the core at 550˚C by multiple, independent and redundant liquid-metal heat pipes. Heat is conducted from the fuel rods through the graphite moderator to the potassium-filled heat pipes. The condenser of each heat pipe protrudes above the reactor core. A secondary organic heat-transfer loop operating at a peak temperature of 370˚C and 5 MPa extracts heat from the heat pipe above the core and converts the thermal energy into electricity. Individual heat pipes act as independent localized cells for passive primary heat transport. This system offers a high level of redundancy due to the many independent heat pipe assemblies in the core. This mitigates the risks in a loss-of-coolant accident (LOCA) as each heat pipe is designed to transport additional thermal energy if an adjacent heat pipe should fail.

3. Potential Heat Pipe Applications for Passive Heat Removal in Nuclear Reactors

In the event of a station blackout, decay heat removal from the containment for an extended period of time is a major concern. Passive long-term decay heat removal from the containment atmosphere can be achieved indefinitely by integrating low temperature heat pipes into the containment design. For conventional containments, the evaporator section of the heat pipes would be exposed to the containment atmosphere while the condenser section would be located outside and cooled by a heat sink such as a large water pool or the atmosphere. Loop heat pipes could be used to minimize the number of penetrations through the containment. In order to minimize heat loss during normal operations, the heat pipes could be designed such that heat removal from the containment atmosphere will only begin once the containment temperature reaches a certain value (i.e. following a loss-of-coolant accident) through appropriate selection of the heat pipe working fluid and heat pipe pressure.

For small reactors it is desirable to have underground containment as it offers additional security. An underground containment significantly reduces the damage risk from external hazards, such as tornados, missiles or aircraft crashes. It also enhances containment of radioactive material in case of an accident. A number of small reactors, including the Nuclear Battery, have been proposed with underground containment. Passive long-term heat removal from the underground containment can be achieved using heat pipes which use the ground or an external underground water source as the heat sink. Compared to the atmosphere and the ground, the underground water source would provide the most efficient passive heat removal [3].

Heat pipes could also be used to passively cool spent fuel bays in nuclear plants. Similar to the containment heat removal options discussed above, the evaporator of the heat pipes could be submerged in the spent fuel pool, while the condenser would reject heat to the atmosphere, the earth, or an external water source. In addition to their passive operation, heat pipes also greatly reduce the risk of leakage into the cooling medium as they use a contained working fluid.

4. Conclusions

Use of heat pipes for passive heat removal in nuclear reactors offer many advantages. They are highly reliable due to passive operation, do not require any external power and typically require no maintenance. Failures of a few heat pipes do not compromise the overall functionality of the system, since they operate independently and are designed to transfer additional heat compared to normal operation. Application of heat pipes in small nuclear reactors is desirable as heat pipe based cooling systems lend themselves to more autonomous operation and make it possible to deal with long-term heat removal (no immediate operator intervention needed in accident scenarios) for small reactors that are located in remote locations.

5. References

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[3] M.M. Razzaque, “On Application of Heat Pipes for Passive Shutdown Heat Removal in Advanced Liquid Metal and Gas-Cooled Reactor Designs,” Ann. Nucl. Energy, Vol 16, 1990.