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# The role of heat pipes in intensified unit operations

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## ABSTRACT

Heat pipes are heat transfer devices that rely, most commonly, on the evaporation and condensation of a working fluid contained within them, with passive pumping of the condensate back to the evaporator. They are sometimes referred to as 'thermal superconductors' because of their exceptionally high effective thermal conductivity (substantially higher than any metal). This, together with several other characteristics make them attractive to a range of intensified unit operations, particularly reactors. The majority of modern computers deploy heat pipes for cooling of the CPU.

The application areas of heat pipes come within a number of broad groups, each of which describes a property of the heat pipe. The ones particularly relevant to chemical reactors are:

i. Separation of heat source and sink.
ii. Temperature flattening, or isothermalisation.
iii. Temperature control.

Chemical reactors, as a heat pipe application area, highlight the benefits of the heat pipe based on isothermalisation/temperature flattening device and on being a highly effective heat transfer unit. Temperature control, done passively, is also of relevance. Heat pipe technology offers a number of potential benefits to reactor performance and operation. The aim of increased yield of high purity, high added value chemicals means less waste and higher profitability. Other intensified unit operations, such as those employing sorption processes, can also profit from heat pipe technology.

This paper describes several variants of heat pipe and the opportunities for their use in intensified plant, and will give some current examples.

## 1. Introduction

The control of chemical processes is becoming increasingly demanding, driven by the necessity to reduce by-products, improve the quality of the chemical being produced, and minimise energy consumption. In some respects intensifying a process step, while offering a number of well-documented advantages [1], can create its own demands in areas such as thermal control if the full benefits of PI are to be realised. PI of reactions for instance is often achieved via enhancing mixing, such that the reaction is no longer mass transfer/mixing limited, and can progress at its "intrinsic" rate. This can be orders of magnitude faster than previously observed rates, so can lead to orders of magnitude increases in the rate of heat release.

There are several ways of controlling temperature in chemical reactions. The integration of heat exchangers and reactors in micro-reactors and similarly-configured larger 'heat exchanger-reactors', allow rapid heat transfer thereby accommodating the large exotherms associated with the high reaction rates achieved in many of these units. Also, heat pipes may be used for cooling duties, as proposed by IMM and collaborators in Mainz, Germany, as illustrated later [2]. For larger plant and bio-reactors the integration of effective heat transfer with reactors is less successful, and if precise control is required the options are few. 'Control' in this context may apply to heat removal, heat input, isothermalisation (to allow spatially uniform reaction) and precise temperature control.

The heat pipe can be a highly effective tool for isothermalising, thermally managing and controlling chemical processes that are exo- or endothermic, whether intensified or not. In its specialised forms, as a variable conductance heat pipe and/or with high gravity fields imposed by rotation, it promises either passive or active control to a degree not possible with other methods, across a wide range of temperatures, (from cryogenic regimes to temperatures at which liquid metals, are used as heat pipe working fluids), and heat fluxes.

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## 2. The heat pipe

### 2.1. The basic heat pipe

A heat pipe [3] is a two-phase liquid–vapour heat transfer device that in its basic form is a sealed tube lined internally with a wick to generate capillary action. The wick is saturated with a working fluid, the choice of which depends upon the operating temperature range, e.g. water is used at 30–200 °C, sodium at 600–900 °C. By evaporation, vapour flow along the pipe, condensation and return of the condensate in the wick, the heat pipe can passively transfer substantial amounts of heat with very small temperature differences between the evaporator and condenser sections, giving the device a very high effective thermal conductivity: several hundred times that of solid copper. A simple heat pipe and its basic liquid/vapour transport, is shown in Fig. 1, below. Note that where a wick is omitted and gravity, or other forces, are used to facilitate liquid transport in the pipe, the device is commonly called a “thermosyphon”. The most prolific use for heat pipes is in controlling the temperature of Central Processors (CPUs) in desktop and laptop computers. The market is millions of units/week.

Heat pipes can also be made in a variety of geometries including annular form e.g. in isothermal reactors/furnaces, and as flat plates.

The small internal temperature differences, regardless of geometry, give some self-sustainable temperature flattening via feedback to any areas outside the heat pipe wall, so peaks/hot spots in a stirred pot reactor can be reduced and e.g. temperature profiles flattened.

### 2.2. The variable conductance heat pipe (VCHP)

The variable conductance heat pipe (VCHP), sometimes called in a specific variant the gas-controlled or gas-loaded heat pipe, has a unique feature that sets it apart from other types of heat pipe. This is its ability to maintain a device mounted at the evaporator at a near constant temperature, independent of the amount of power being generated by the device. Variable conductance heat pipes are now routinely used in many applications. These applications range from thermal control of components and systems on satellites to precise temperature calibration duties [8] and conventional electronics temperature control. Their use in chemical plants would be novel, although they are proposed for use in nuclear reactors [4].

The temperature control functions of a gas-buffered heat pipe were first observed as a result of non-condensable gas generation within a sodium/stainless steel basic heat pipe – in effect a failure mode. It was observed [3] that as heat was put into the evaporator section of the heat pipe, the hydrogen generated was swept to the condenser section. An equilibrium situation shown in Fig. 2 was reached. Subsequent visual observation of high-temperature heat pipes, and temperature measurements, indicated that the working fluid vapour and the non-condensable gas were segregated, that a sharp interface, with minimal diffusion, existed between the working fluid and the non-condensable gas and that the non-condensable gas effectively blocked off the condenser section (RHS in Fig. 2) it occupied, stopping any local heat transfer. Significantly, it was also observed that the non-condensable gas interface moved along the pipe as a function of the thermal energy being transported by the working fluid vapour, and it was concluded that suitable positioning of the gas interface could be used to control the temperature of the heat input section (evaporator – LHS) within close limits. Most interestingly, it was found that that crude but effective control could be achieved in a totally passive manner in this basic heat pipe.

The type of VCHP described above is of the passively controlled type. The active condenser length varies in accordance with temperature changes in various parts of the system – see Fig. 3. An increase in evaporator temperature causes an increase in vapour pressure of the working fluid, which causes the gas to compress into a smaller volume, releasing a larger amount of active condenser length for heat rejection. Conversely, a drop in evaporator temperature results in a lower vapour surface area. The net effect is to provide a passively controlled variable condenser area that increases or decreases heat transfer in response to the heat pipe vapour temperature.

### 2.3. Feedback control applied to the VCHP

Much of the subsequent work on heat pipes containing non-condensable or inert gases has been in developing means for controlling the positioning of the gas front, and in ensuring that the degree of temperature control achievable is sufficient to enable components adjacent to the evaporator section to be operated at essentially constant temperatures, independent of their heat dissipation rates, over a wide range of powers.

The first extension of the simple form of gas-buffered pipe shown in Figs. 2 and 3 was the addition of a reservoir downstream of the condenser section. This was added to allow all the heat pipe length to be effective when the pipe was operating at maximum capability and to provide more precise control of the vapour temperature. The reservoir could also be conveniently sealed using a valve. The early workers in the field of cold-reservoir VCHP’s were

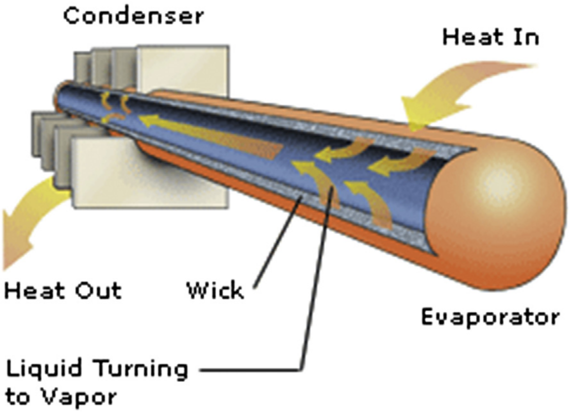

**Fig. 1.** A tubular heat pipe (Courtesy Thermacore Ltd.).

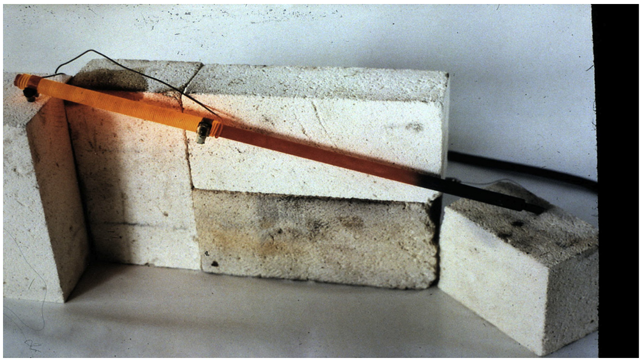

**Fig. 2.** A liquid sodium heat pipe, showing the non-condensable gas (RHS), the sharp interface between that and the hot vapour, and, incidentally, the capillary ‘pump’ operating to return liquid sodium against gravity to the evaporator (LHS).