

# Passive Heat Exchanger Temperature Control Using Variable Conductance Heat Pipes

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## Abstract

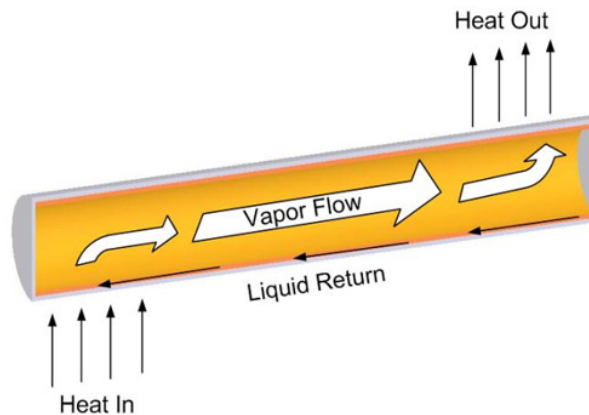
Heat exchangers are important unit operations for a variety of industrial processes. They are often necessary to recuperate waste heat and improve process efficiencies. The heat exchanger's outlet streams often feed processes that are very sensitive to temperature (chemical reactors, separation membranes, fuel cells, etc.) where robust temperature control is a must. Most heat exchangers maintain outlet temperatures by using active means such as temperature controllers with actuated valves and inefficient by-pass streams to maintain a set point. These active control schemes have several drawbacks including the low reliability of moving parts, susceptibility to operator error, and the complicated systems level modeling required to validate control schemes.

Presented in this paper is a passive temperature control technology that utilizes variable conductance heat pipes (VCHP) to control outlet temperature from a counter current heat exchanger. VCHP's are heat pipes filled with a prescribed amount of non-condensable gas. The non-condensable gas expands and contracts in the condenser of the heat pipe as the saturated working fluid's vapor pressure and temperature changes. As a result, the evaporator temperature of the VCHP is nearly constant, regardless of operating conditions (flow rates, inlet temperatures, etc.). A heat exchanger using a tube bank of VCHP's has the unique property that the hot side fluid exits at nearly constant temperature regardless of heat exchanger operating conditions (hot and cold side inlet temperatures and flow rates.) A transient model for a VCHP heat exchanger is presented along with experimental data from a VCHP heat exchanger designed to control the outlet temperature of a hydrogen stream for a fuel cell application. The passive temperature control feature of VCHP heat exchangers is ideal for applications where reliability and safety are of paramount concern.

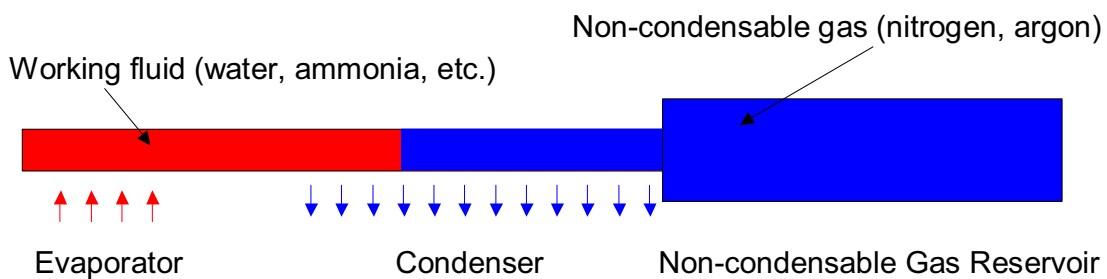
## Background

Heat pipes passively transfer heat at low thermal resistances by capillary circulation of fluid at saturated conditions[1]. Shown in Figure 1, a heat pipe consists of a vacuum leak tight envelope enclosing a working fluid and wick structure. Heat input vaporizes the saturated liquid contained within the wick in the evaporator section of the heat pipe. The vapor, carrying the latent heat of vaporization, flows towards the cooler condenser section. In the condenser, the vapor condenses within the wick, giving up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. Fluid circulation continues as long as the temperature gradient between the evaporator and condenser is maintained. The heat transfer process occurs with minimal temperature gradient between the evaporator and condenser because the saturated fluid within the heat pipe circulates with small pressure differences. Since the fluid is at saturated conditions, small pressure differences correlates to small temperature differences.

A variable conductance heat pipe (VCHP) is a variation of a heat pipe possessing some inherent temperature control abilities[2]. Variable conductance heat pipes get their temperature control features from the expansion and contraction of non-condensable gas in the condenser of the heat pipe. At low temperatures, the heat pipe working fluid exerts a low pressure on non-condensable gas in the condenser of the heat pipe, causing the non-condensable gas to expand. A conceptual diagram of a variable conductance heat pipe operating at a low temperature condition is shown in Figure 2. At this low temperature condition most of the condenser is blocked off by the non-condensable gas, which prevents the heat pipe working fluid from cooling itself down further. As the thermal load on the heat pipe is increased, the heat pipe working fluid temperature increases, along with pressure. As shown in Figure 3, the non-condensable gas contracts to expose more of the condenser area for cooling. As the gas expands, the conductance (inverse of thermal resistance) of the heat pipe is increased. The increase in conductance with temperature gives the variable conductance heat pipe the ability to maintain a temperature around a given set point. The set point is chosen by charging the heat pipe with an exact amount of non-condensable gas.



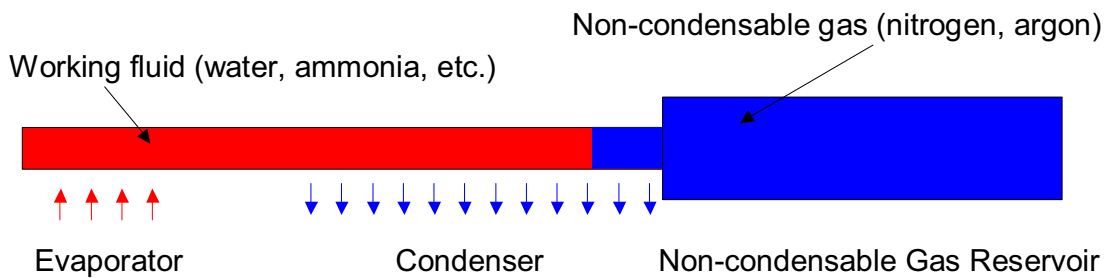
**Figure 1** A schematic of a heat pipe is shown. Heat entering the evaporator of a heat pipe boils fluid out of a wick structure. Vapor flows axially down the inner diameter of the heat pipes and condenses. The wick structure then returns fluid back to the evaporator.



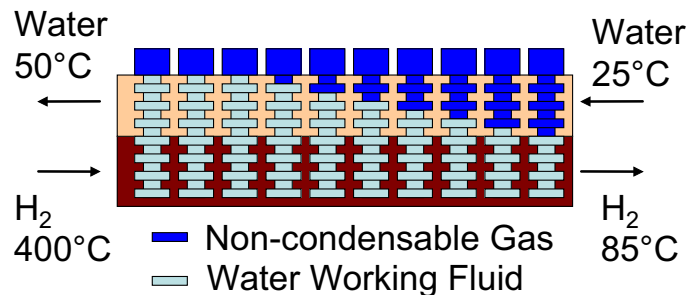
**Figure 2** A diagram of a variable conductance heat pipe operating at a low temperature condition is shown. With the saturated working fluid at low saturated temperature (and saturated pressure) the non-condensable gas present in the reservoir expands to occupy most of the condenser section.

## Variable Conductance Heat Pipe Heat Exchanger

A variable conductance heat pipe heat exchanger (VCHP HX) is an array of variable conductance heat pipes in a heat exchanger configuration[3-4]. A diagram of a VCHP HX with operating conditions for a Navy fuel cell application is shown in Figure 4 [5-6]. The hot side fluid (hydrogen in this example) enters the heat exchanger and passes over the evaporator side of the variable conductance heat pipe elements. Coolant flows counter currently to this stream and passes over the condenser end of the heat pipes. Nearest to the hot side inlet, the heat pipes are the hottest. The non-condensable gas is compressed, leaving most of the condenser available to efficiently transfer heat to the coolant side. In this region of the heat exchanger the highest heat transfer rates occur. As the hot side fluid flows toward the exit of the heat exchanger it cold down. The local heat pipes also decreases in temperature, expanding non-condensable gas and “blanketing” the condenser of the heat pipe. As the hot side fluid approaches the exit, the condenser is almost completely blocked by non-condensable gas, and heat transfer rates approach zero. The hot side outlet temperature then exits the heat exchanger at approximately the set point of the variable conductance heat pipe elements.



**Figure 3** A diagram of a variable conductance heat pipe operating at a high temperature condition is shown. With the saturated working fluid at high saturated temperature (and saturated pressure) the non-condensable gas present in the reservoir compresses to occupy most of the condenser section.



**Figure 4** A variable conductance heat pipe (VCHP) heat exchanger is shown. Essentially an array of individual heat pipes, the VCHP heat exchanger passively responds to changes in inlet process temperatures by altering available condenser area on the cold fluid side. As a result, hot side outlet temperatures remain nearly constant. Operating conditions for a hydrogen fuel cell application are shown.

The advantage of the VCHP HX is that outlet hot side temperature is passively controlled. As the hot side inlet temperature or flow rate changes, the outlet of the hot side temperature side remains constant due to the expansion and contraction of non-condensable gas in the condensers of the heat pipes. If an operating condition requiring more thermal duty (such as increased inlet temperature or higher flow rate) is encountered the heat pipes in the heat exchange will rise slightly in temperature. Non-condensable gas in the heat pipes will contract, exposing more condenser and increasing the thermal duty of the heat exchanger. The result is a relatively constant outlet hot side temperature.

### VCHP Heat Exchanger Modeling

The following summarizes a model developed to transiently model the VCHP HX. Nomenclature is provided after the conclusion section. Equations 1 and 2 describe the time and position dependent energy balances for the process fluid and steam in the heat exchanger. The process fluid exchanges heat with the local heat pipe at its current temperature. The necessary heat transfer coefficient is not that of the heat transfer coefficient on the heat pipe surface, but the effective heat transfer coefficient observed across the footprint of the heat exchanger. An equation for the effective heat transfer coefficient is shown in Equation 3. Equation 4 describes the time and position dependent heat balance around the heat pipe, accounting for the mass of the heat pipe. The heat pipe exchanges heat with the local process streams. The area of the heat pipe on the condenser side is sensitive to local process conditions and heat pipe properties such as geometry and non-condensable gas charging. The area for heat transfer on the condenser side is a function of the non-blanketed condenser length and amount of heat conducted up the heat pipe wall. The equation describing the length of non-condensable gas covered condenser is displayed in Equation 5. Equation 6 describes the effective length of open condenser accounting for the conduction up the heat pipe wall in the non-condensable gas covered condenser length. Equation 8 describes a non-dimensional fin efficiency parameter for conduction through a pin (in this case a hollow pin). This model is capable of predicting both transient and steady state performance for the VCHP HX. Steady-state predictions are compared to experimental data in Figures 5 and 6.

$$\frac{\partial T_1}{\partial t} = -v_1 \frac{\partial T_1}{\partial x} + \frac{h_{1,eff}}{(\rho C_p H)_1} (T_{HP} - T_1) \quad (1)$$

$$\frac{\partial T_2}{\partial t} = -v_2 \frac{\partial T_2}{\partial x} + \frac{h_{2,eff}}{(\rho C_p H)_2} (T_{HP} - T_2) \quad (2)$$

$$h_{n,eff} = h_n \frac{A_n}{W^2} \quad (3)$$

$$\frac{\partial T_{HP}}{\partial t} = \frac{h_1 A_1 (T_1 - T_{HP}) + h_2 A_2 (T_2 - T_{HP})}{(m C_p)_{HP}} \quad (4)$$

$$L_{2,ncg} = \frac{\frac{n_{ncg} T_{ncg} R}{P_{Sat,HP}} - V_R}{\pi R_{HP}^2} \quad (5)$$

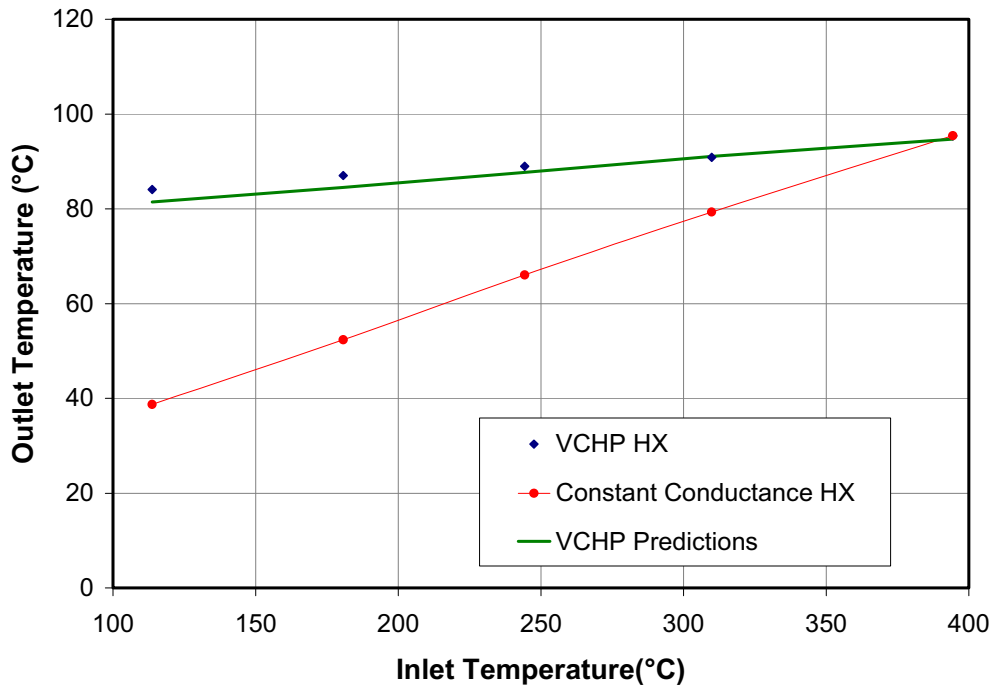
$$L_2 = L_{cond} - L_{2,ncg} + \frac{\tanh(mL_{2,ncg})}{m} \quad (6)$$

$$L_1 = L_{evap} \quad (7)$$

$$m^2 = \frac{h_2 P}{kA_c} \quad (8)$$

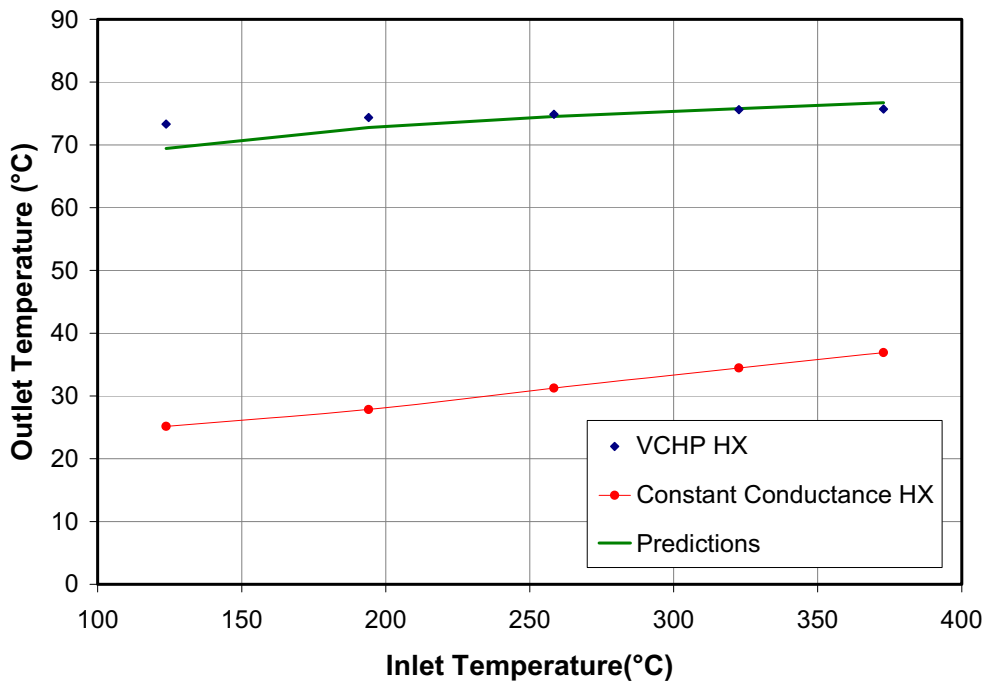
### Experimental Data

A VCHP HX heat exchanger was successfully fabricated and tested. The heat exchanger was tested over a range of operating conditions to verify thermal control. The hydrogen flow rate was varied from 2.5kg/hr down to 0.5kg/hr. The hydrogen inlet temperature was also varied from 400°C down to 120°C. These particular design requirements were supplied from a Navy fuel cell reforming application. The water flow rate was kept constant at 800ml/min. A plot of hydrogen outlet temperature versus hydrogen inlet temperature at the maximum flow rate of 2.5kg/hr is shown in Figure 5. The outlet temperature varied 11°C over the change in inlet temperature from 95°C to 84°C. As expected the heat exchanger operated hotter than the set point under these conditions since the most thermal loading on the heat exchanger is encountered at the highest flow rate. The VCHP heat exchanger model predicted the measured data well. Also shown on the graph is the predicted performance for a typical counter current heat exchanger (non-VCHP, constant conductance) without temperature control. The predicted change in temperature for a typical heat exchanger under these operating conditions would be 56°C.



**Figure 5** The measured outlet hydrogen temperature is plotted against inlet hydrogen temperature for the finless heat exchanger at a mass flow rate of 2.5kg/hr. The predicted outlet temperature from the VCHP heat exchanger model is also shown. The calculated performance for a constant conductance heat exchanger (standard heat exchanger) is also shown.

The results for the 0.5kg/hr testing are shown in Figure 6. The comparison to the typical heat exchanger is also shown. Overall, the VCHP is able to keep the outlet hydrogen temperature within a 22°C temperature range over a 5:1 turndown ratio in flow rate and 280°C change in inlet temperature. The size of the heat exchanger used to make the prediction is the same size used to make the predictions in Figure 5. In other words the size of the heat exchanger used in the prediction was large enough to remove enough heat to maintain the hydrogen outlet temperature of 95°C at 400°C inlet temperature and 2.5kg/hr. For the prediction made in Figure 6, the only variable that needed to be accounted for was the change in heat transfer coefficient due to the lower flow rate.



**Figure 6** The measured outlet hydrogen temperature is plotted against inlet hydrogen temperature for the finless heat exchanger at a mass flow rate of 0.5kg/hr. The predicted outlet temperature from the VCHP heat exchanger model is also shown. The calculated performance for a constant conductance heat exchanger (standard heat exchanger) is also shown.

### Conclusions

A variable conductance heat pipe heat exchanger has been successfully designed, fabricated and tested for a Navy fuel cell application. A performance prediction model for the VCHP HX was verified using experimental data. The experimental data also verified the overall ability of the VCHP HX to passively maintain temperature control under real world design requirements. The VCHP HX is also expected to have benefits in other applications, such as temperature control in chemical reactors where local temperature control is desired.

## Acknowledgements

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## Nomenclature

$A_1$	Area of heat pipe evaporator
$A_2$	Area of heat pipe exposed to working fluid
$Cp_1, Cp_2$	Heat capacity of hot and cold streams
$Cp_{HP}$	Heat capacity of heat pipe (envelope and working fluid)
$h_1, h_2$	Local heat transfer coefficient of hot and cold streams
$h_{1,eff}, h_{2,eff}$	Local effective heat transfer coefficient, normalized by heat pipe footprint
$H_1, H_2$	Height of flow passage on hot and cold side
$m_{HP}$	Mass of heat pipe (envelope and working fluid)
$P_{sat}$	Saturation pressure of working fluid
$R$	Ideal gas constant
$R_{HP}$	Heat pipe outer radius
$R_R$	Radius of non-condensable gas reservoir
$t$	Time
$T_1, T_2$	Temperature of hot and cold streams
$T_{HP}$	Heat pipe temperature
$T_{ncg}$	Non-condensable gas temperature
$T_\infty$	Ambient temperature around reservoir
$v_1, v_2$	Velocity of hot and cold streams
$V_c$	Volume of non-condensable gas in condenser
$V_r$	Volume of reservoir
$x$	Position along heat exchanger
$\rho_1, \rho_2$	Density of hot and cold streams

## References

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