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PRESSURE CONTROLLED HEAT PIPE BASED HEAT EXCHANGER FOR DYNAMIC PROCESS HEAT EXTRACTION CONTROL FOR NUCLEAR POWER PLANTS

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ABSTRACT

Nuclear power plants (NPP) are clean energy sources typically designed for baseload power operations but usually incapable of dynamic operations. One method to improve the NPP flexibility is dynamically extracting process heat. Conventional heat exchangers for heat extraction may be less suitable due to potential for tritium migration into the process stream. This study discusses a novel heat exchanger (HX) based on Pressure Controlled Heat Pipe (PCHPs) that ensures faster responses to varying heat load and mitigates challenges typical to conventional heat exchangers. Thermosiphons were used here as a PCHP. To demonstrate this technology, a prototype PCHP-HX was fabricated with stainless steel 304. The main stream heat from the NPP and the process heat were divided into two shells and connected by a bundle of PCHP tubes. The dynamic response to heat load switching was achieved by introducing Non-Condensable Gas (NCG) into the thermosiphons. Within the given operating conditions, the PCHP-HX demonstrated up to 6.5 kW of heat transfer. When NCG was added, system shutdown, was achieved within 7 minutes. When NCG was evacuated, complete system start-up was achieved within 4 minutes with 100% heat delivery.

Keywords: Nuclear energy, power plant flexibility, heat pipe, thermosiphon, Variable Conductance Heat Pipe (VCHP), Pressure Controlled Heat Pipe (PCHP)

NOMENCLATURE

HX	Heat Exchanger
L/min; GPM	Liters per minute; Gallons per minute
NPP	Nuclear power plants
PCHP	Pressure Controlled Heat Pipe
VCHP	Variable Conductance Heat Pipe

1. INTRODUCTION

Nuclear power provides about 10% of the world's electricity demand, from 450 nuclear power reactors, in over 30 countries [1]. Nuclear power is a clean power source and established for baseload power generation. The operational aspects are well known, in that the nuclear reaction generates heat in the reactor core. The heat is transmitted from the reactor core fluid to the steam generator. The steam from the generator is used to drive the turbine to produce power.

The steam exiting the turbine has potential to deliver process heat, which could increase the Nuclear Power Plant (NPP) flexibility and economic viability. The process heat can drive applications requiring process temperatures 50 °C or higher [2]. One example of process heat is hot water supply, 100s of miles away at competitive costs. This has been applied in countries like Russia, China, Switzerland, Finland, etc. [3]. Simple thermal system integration strategies like placing a heat exchanger for extracting residual heat from the turbine exhaust can be implemented for process heat extraction [4]. A conventional approach for process heat extraction is using shell and tube heat exchanger or plate heat exchangers [5, 6]. In the shell and tube heat exchanger, hot main fluid with residual heat usually flows through the tubes and the cold process stream flows in the shell. Plate heat exchangers have brazed metal plates stacked in parallel to form shells containing a patterned network of tubing for non-mixing but high heat transfer between the fluids. While, these conventional approaches have high applicability, they suffer from following major limitations:

- The high heat capacity of the structures along with fluid flow results in slow transient response to operation- i.e., slow start-up, delayed shutdown, etc.
- The hot main fluid and the cold process fluid are separated by thin metallic walls. Nuclear industry is concerned with tritium (contaminant) migration from the hot fluid (as it is in the nuclear reactor zone) into the process stream [7].
- To alleviate the above concerns to some extent, valves for flow control must be used control the stream flow. These valves are associated with

excessive pressure drops, which could lead to an increase in parasitic power consumption.

These limitations hinder the flexibility of dynamically with fast heat extracting and shutting down process from NPP with conventional heat exchangers. One method to alleviate the above concerns is using heat pipe-based heat exchangers (HPHX) [8]. HPHX have fast response since the heat pipes basically are hollow tubes with enclosed two-phase working fluid transporting heat from the heat source to the sink. These heat exchangers have been found to be highly feasible for process (waste) heat recovery applications [9, 10]. Here, the hot main fluid and the cold process fluid are in separate shells and the heat transfer is by the bundle of heat pipe tubes connected to the two shells. Tritium migration is lower compared to conventional heat exchanger since there are two shells involved. This can be further reduced by incorporating Variable Conductance Heat Pipes (VCHPs), which have a column of NCG. The tritium, can be swept away by the NCG during the addition and the removal steps. This manuscript shows a VCHP based HX for fast thermal response and the aspect of tritium migration is not discussed here. The VCHP mode was achieved by controlling the pressure of NCG in the heat pipe (thermosiphon was used here for simplicity).

To enable process heat extraction from NPPs, a novel Heat Exchanger (HX) was demonstrated utilizing Pressure Controlled Heat Pipes (PCHP) as a passive heat delivery medium between main stream and process heat shells. A bundle of thermosiphons in a circular arrangement were used as PCHPs. Heat pipes have a wick structure to aid liquid return by capillary, while, in thermosiphon, there are no wicks, so liquid return is by the action of gravity. The constructional features and demonstration of the PCHP-HX are discussed in the manuscript.

2. Description and Demonstration of PCHP-HX

2.1 Description of PCHP

A heat pipe or a thermosiphon is a two-phase passive heat transfer device with a very high thermal conductivity. The heat applied on one end (called evaporator) vaporizes the enclosed working fluid, which then flows to the heat rejection end (called condenser). The vapor condenses and returns by capillary action of the wicks (in heat pipes) or by action of gravity (in thermosiphon). A Variable Conductance Heat Pipe (VCHP) can modulate the operation of the heat pipe (or thermosiphon) by pushing the NCG into the condenser. This can be obtained by two methods – by heating the NCG reservoir or by increasing the pressure of the NCG in the reservoir. The heat pipe with the latter mode of operation is referred to as a PCHP [11]. In this manuscript, a thermosiphon was constructed and demonstrated as a PCHP.

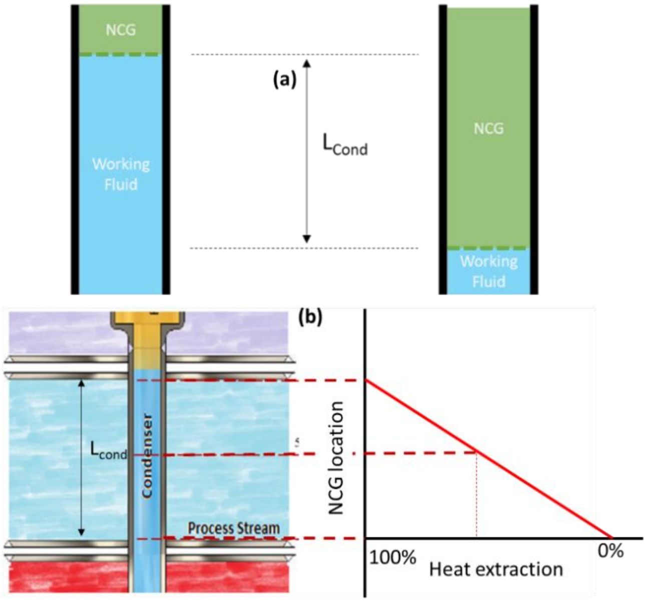

Figure 1. (a) Graphic illustration of NCG occupying condenser section of thermosiphon; (b) Illustration of influence of NCG location in thermosiphon on process heat extraction

Figure 1 shows the schematic of illustration of NCG location and its influence on heat extraction in the thermosiphon. The conductance of the thermosiphon, and thus, the process heat extraction rate, can be controlled by controlling the NCG content in the condenser section of the thermosiphon. For illustration, the NCG location in the thermosiphon is mapped on to the vertical scale and the process heat extraction is mapped on to the horizontal scale in Figure 1 (b). When, the NCG is in the reservoir and the entire length of the condenser is available for heat delivery by the working fluid, then 100% heat extraction is obtained. As the NCG is pushed into the condenser, heat extraction rate reduces by proportional rate. When the NCG fully occupies the condenser, the thermosiphon working fluid cannot access the condenser for heat deliver any more, and thus no heat can be extracted. As a consequence, when NCG blocks the condenser, the evaporator temperature of the thermosiphon approaches the main stream temperature, while, the condenser end of the thermosiphon approaches the process stream temperature.

2.2 Construction of PCHP-HX

A conventional HX design considered in NPP uses shell and tube configuration where the main stream and process stream flows are separated by the tube-wall construction. The PCHP-HX, on the other hand, separates the main and process stream flows with two separate shells connected by a bundle of thermosiphons in a circular arrangement. The main stream flows from the bottom shell and the process stream flows through the top sell.

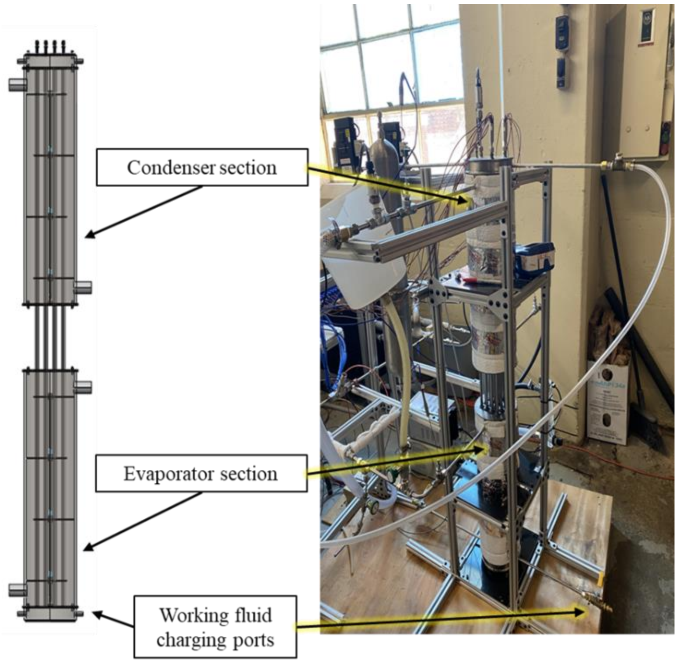

Figure 2. PCHP-HX experimental system

Table 1. Geometric features of PCHP-HX

Thermosiphon tube Details	
Number of thermosyphons	16
Material	SS-304
Working fluid	Water
Length of the thermosyphon	1.22 (m)
Outer diameter of the thermosyphon	9.5 (mm)
Tube thickness of the thermosyphon	0.89 (mm)
Length of the thermosyphon tube in the evaporator section	0.51 (m)
Length of the thermosyphon tube in the condenser section	0.51 (m)
Effective heat transfer area between shell and tube	0.29 (m^2)
Non-condensable gas (NCG)	Air
Shell Details	
Material	SS-304
Outer diameter of the shell in the evaporator section	0.15 (m)
Outer diameter of the shell in the condenser section	0.15 (m)
Thickness of the shell wall	1.65 (mm)
Main stream fluid	Water
Process stream fluid	Water

Figure 2 shows the assembled prototype PCHP-HX experimental system, whose geometric features are described in Table 1. The shell and PCHP tubes were constructed with stainless steel (SS-304). A total of 16 thermosiphon tubes of length 1.22 m and diameter 9.5 mm were constructed and connected in parallel to the working fluid reservoir at the bottom and a common NCG reservoir at the top. The thermosiphons were arranged in a circular pattern and the main stream and process stream shells were then welded to the tubes. The working fluid, i.e., DI water was charged after vacuuming the thermosiphons. Air was used as the NCG to control and demonstrate the operation of the PCHP. To demonstrate the shutdown, air was introduced into the condenser sequentially by allowing a small volume of air over a short period of time. The startup was demonstrated by evacuating air from the thermosiphons using a vacuum pump.

Figure 3 shows the experimental methodology used for the demonstration of the PCHP-HX. A main stream inlet temperature was maintained at a constant temperature by using a pressurized water heater capable of delivering up to 9 kW heat. The temperature at the inlet was kept constant between 80-100 °C by using a temperature feedback loop. Cold tap water at inlet temperature of 14±1 °C was used as the process stream. The main stream delivers heat to the evaporator section of the thermosiphons and exits the shell and flows back into the heater in a closed loop. Ten thermocouples were attached to the middle thermosiphon vertically to ascertain the temperature profile during the PCHP operation during both active condenser and inactive condenser modes. Active condenser mode is when there is no NCG in the condenser and all heat is delivered to the process stream; while, inactive condenser mode is when NCG is in the condenser, and a part or the whole of the condenser is inactive, thereby, restricting heat delivered to the process stream.

Firstly, the isothermal behavior of the thermosiphon was determined by maintaining the main stream temperature between 80 °C to 100 °C. The heat extraction by the process stream was determined by maintaining the process stream flow rate between 1.2 L/min (~0.2 GPM) to 3.8 L/min (~1 GPM). For all the experiments, the mainstream flow rate was maintained at 3.8 L/min (~1 GPM). Then the PCHP mode was demonstrated with description of the temperature profile of the thermosiphon and the main and process streams. The system startup and shutdown profiles were then demonstrated to show fast transient response for operational feasibility in NPP.

3. RESULTS AND DISCUSSION

3.1 Heat Transfer Characterization of Thermosiphon

To ascertain isothermal profile of the thermosiphon, experiments were performed at main stream temperatures of 80 °C, 90 °C, and 100 °C. The thermosiphon did not have any NCG and the condenser length was fully active for heat transfer.

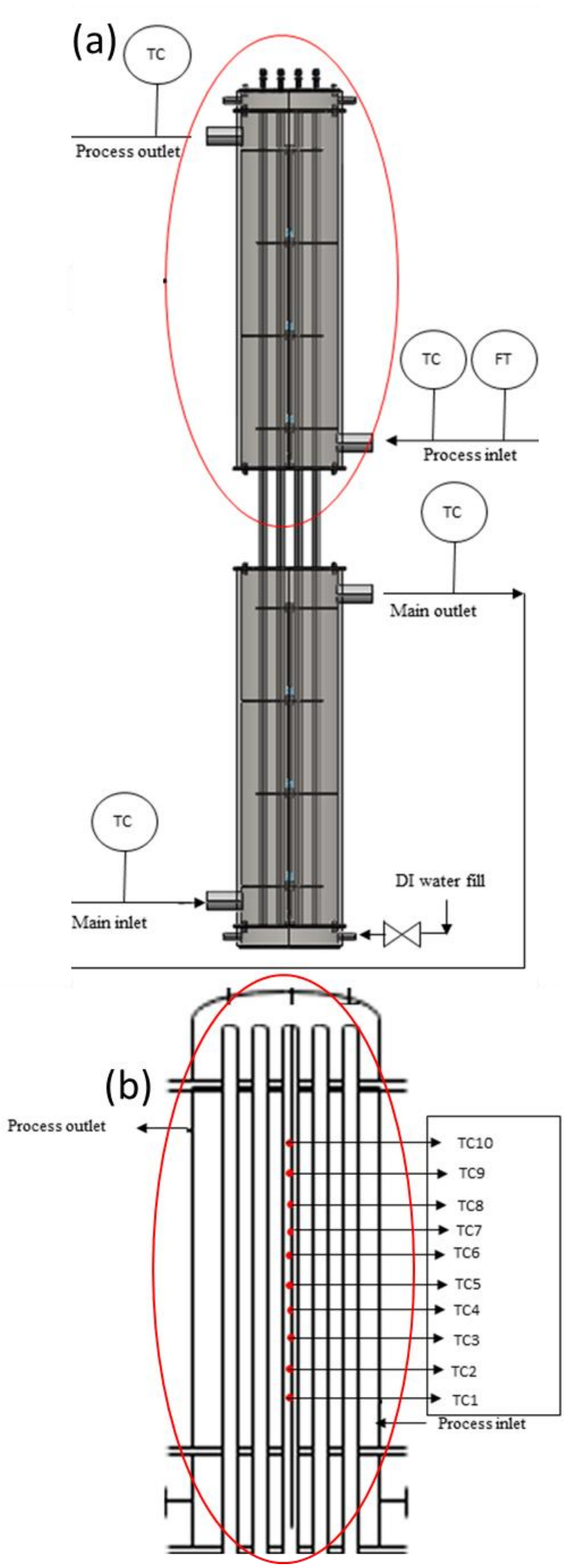

Figure 3. (a) Experimental methodology for demonstration of PCHP-HX. TC &PT indicate – thermocouple and pressure transducer. (b) Location of thermocouples on the condenser section in the process stream shell

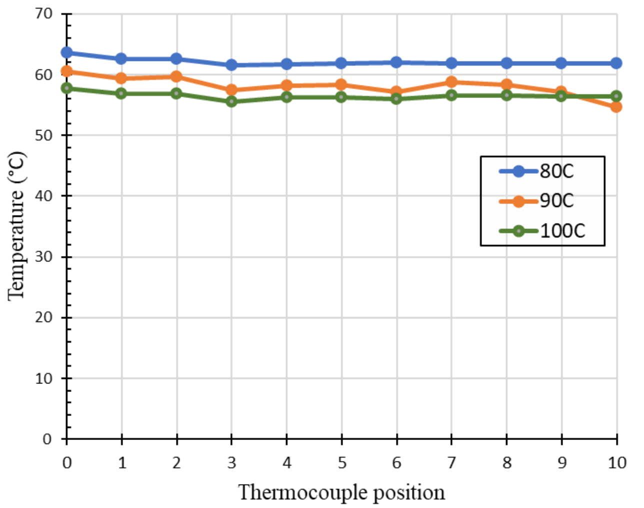

Figure 4. Isothermal profile of active thermosiphon. No NCG was present in the condenser during this characterization test.

Figure 4 shows temperature profile of the thermosiphon, at all 10 different thermocouple locations on the thermosiphon in the process stream section. At main stream temperature of 80 °C, the process stream flow rate was 1.2 L/min, while, for the other two cases, the process stream flow rate was 3.8 L/min. In all three cases, isothermal profile was observed in the thermosiphons, indicating two-phase operation.

3.2 Influence of Process Stream Flow Rate on Heat Extraction

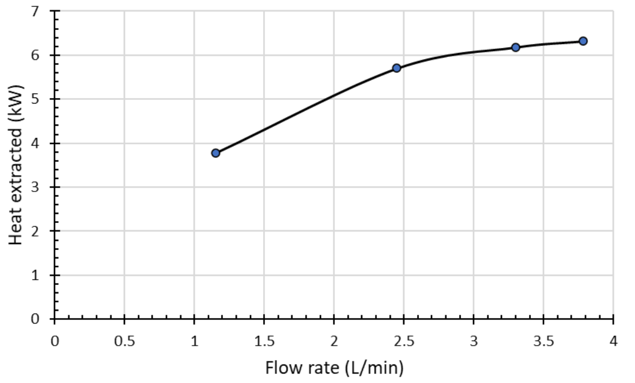

Figure 5. Influence of process stream flow rate on heat extraction rate

Figure 5 shows influence of process stream flow rate on heat extraction rate. As flow rate increases from above 1.2 L/min to above 3 L/min, the fluid flow and heat transfer properties develop. As the flow rate reached 3.8 L/min, a well-developed fluid flow and heat transfer properties were obtained, thereby, obtaining a steadier heat transfer rate. The peak heat extraction rate at 3.8 L/min was approximately 6.3 kW.

The uncertainty in heat extraction rate was determined based on the measurement device accuracy was computed as shown in Table 2.

Table 2. Uncertainty of measurement

Device/ Output	Value	Error
Cold process fluid inlet temperature	14 °C	0.5 °C
Cold process fluid outlet temperature	37.9 °C	0.5 °C
Flow rate	3.8 L/min	2%
Heat extraction rate	6.3 kW	0.23 kW

3.3 Influence of NCG on PCHP-HX Process Heat Transfer

An experiment with controlled NCG addition and evacuation was performed on the PCHP-HX and the heat transfer characteristics were determined.

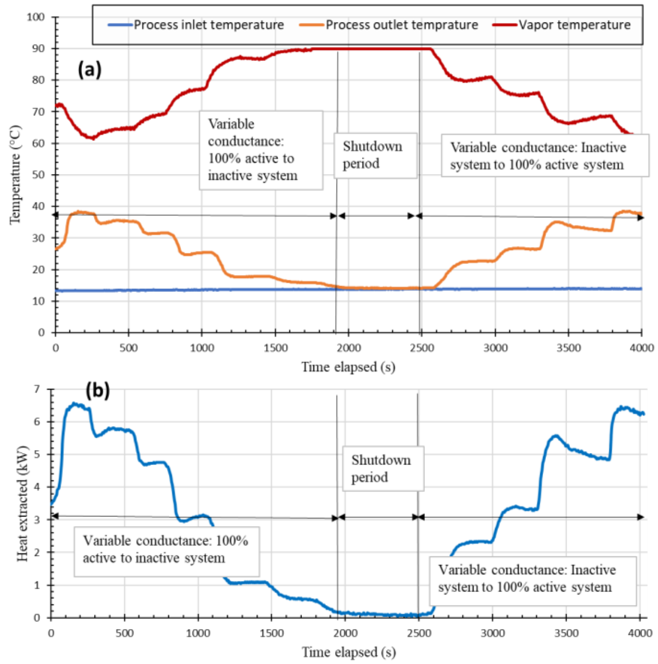

Figure 6. (a) Temperature profile of the process stream and anticipated vapor temperature; and (b) heat extracted during sequential NCG addition and evacuation

Figure 6 shows temperature profile and heat extraction rate obtained at the process stream with sequential NCG addition and evacuation. As NCG blocks the condenser, a portion of the condenser becomes inactive, while, only the condenser length accessible by the working fluid can deliver heat. As such, the process heat delivery reduces. As a consequence, this results in an increase in evaporator and working fluid temperature in the thermosiphon. The first step in Figure 6 shows sequential NCG addition. Figure 7 shows schematic illustration of NCG location in the condenser section during different stages of NCG addition. When the condenser was fully active, 6.5 kW of process heat was extracted with corresponding process stream outlet temperature reaching 38.1 °C. As NCG concentration increased, the active condenser length decreased. As a result, a fast drop in process outlet stream temperature and heat transfer rate was observed. After 1900 s, as NCG filled the condenser, heat extraction stopped. The small value of heat extraction noticed could be due to instrument errors, but the value was less than 0.1 kW, and thus, inconsequential. This stage, the shutdown period, was allowed to exist for some time until 2500 s. After this, the small amounts of NCG was evacuated from the thermosiphons by a vacuum pump. As NCG concentration reduced, the thermosiphon fluid temperature reduced and the process stream temperature increased indicating an increase in the heat delivery rate. As the NCG was fully evacuated, conditions similar to the first step before NCG addition was obtained with more than 6.5 kW of heat delivery to the process stream.

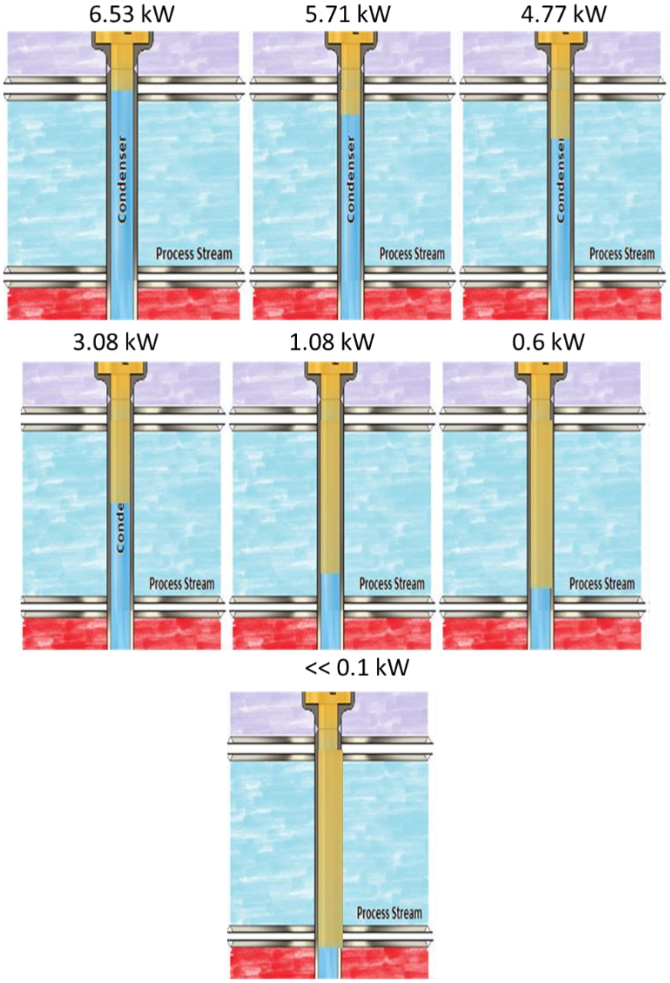

Figure 7. Schematic illustration showing NCG location in the condenser section of the thermosiphon during different stages of NCG addition. The NCG location and the active condenser section is not to scale and used here only for representation.

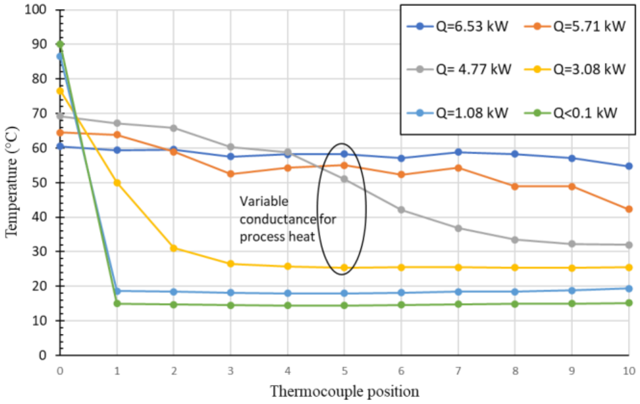

Figure 8. Temperature profile of PCHP- condenser during different stages of NCG addition

To further discuss the NCG behavior on the PCHP operation, the quasi-steady state instantaneous temperature profile along the condenser section is shown in Figure 8. Thermocouple '0' refers to anticipated vapor/ working fluid temperature inside the PCHP. When the PCHP is fully active, approximately 6.5 kW of heat was delivered to the process stream and all the thermocouples had an isothermal profile at temperatures approximately ~ 60 °C, except for a small dip at the last thermocouple at 55 °C. As NCG concentration increased, a small upward shift in vapor temperature was noticed along with the deviation from isothermal profile. For example, for NCG concentration enabling 4.77 kW of heat transfer, a clear drop in temperature profile from thermocouples 4 to 6 can be noticed, likely indicating the fluid location and the NCG location. As NCG concentration increased in the condenser, all thermocouples in the condenser showed temperature equivalent to the process stream inlet temperature, thus, indicating heat transfer shutdown.

3.4 Transient response of PCHP-HX for NPP process heat control

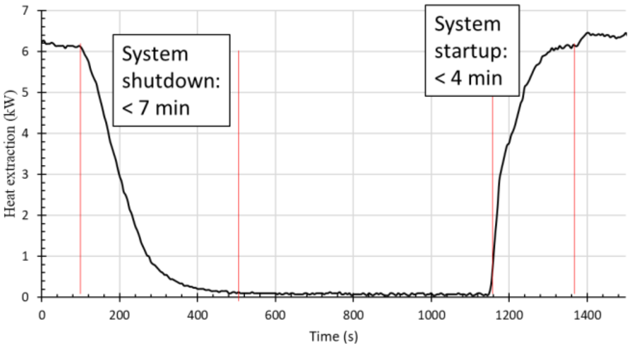

Figure 9. Transient response of the PCHP-HX showing system shutdown and startup behavior

An experiment was performed to determine dynamic response of the PCHP-HX to enable fast response to startup and shutdown of heat transfer for NPP process heat transfer flexibility. Figure 9 shows the transient response of the PCHP-HX during NCG addition and evacuation. The first stage from 100 s shows shutdown curve of the PCHP-HX due to NCG addition from 100% active condenser. NCG was added in small incremental steps but in small time intervals. Complete system shutdown was achieved before 500 s, i.e., approximately 7 minutes. The system was kept in the inactive mode, i.e., condenser filled with NCG, for about 10 minutes. Then NCG was evacuated around 1160 s with a vacuum pump. As NCG was removed, the thermosiphons became active and the system achieved startup with 100% active condenser length within 4 minutes.

4. CONCLUSION

A Pressure Controlled Heat Pipe (PCHP) based Heat Exchanger (HX) was demonstrated as a process heat extraction system enabling improvement in flexibility of operation of Nuclear Power Plants (NPPs). The PCHPs-HX basically consisted of two shells separating main stream flow and the process stream flow. The main stream simulates steam or hot water exiting the turbine of the power plant, and the process stream flow recovers heat from the main stream. The heat transfer was enabled by the PCHPs, which was, an array of SS-water thermosiphons with NCG. The prototype system had about 6.5 kW of heat transfer capability with the selected experimental conditions. Control over heat transfer rate was achieved by controlling the NCG concentration within the thermosiphons, either by adding NCG or evacuating NCG. When NCG was added, the process heat transfer rate reduced, eventually reaching zero when the whole length of the condenser was filled with the NCG. The prototype system showed full system shutdown, i.e., heat transfer shutdown due to NCG addition, within 7 minutes and startup to rated heat transfer rate within 4 minutes of NCG evacuation. The fast transient response of the PCHP-HX shows that the system is capable of enabling process heat control to improve flexibility of NPP operation.

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