Sector Rotating Heat Pipe With Interconnected Branches and Reservoir for Turbomachinery Cooling

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Heat pipe technology offers a possible cooling technique for structures exposed to high heat fluxes, as in turbomachinery such as compressors and turbines. However, in its current configuration as single heat pipes, implementation of the technology is limited due to the difficulties in manufacturability and costs. Hence, a study to develop a new radially rotating (RR) heat pipe system was undertaken, which integrates multiple RR heat pipes with a common reservoir and interconnected braches for a more effective and practical solution to turbomachinery cooling. Experimental study has shown that the integration of multiple heat pipe branches with a reservoir at the top is feasible. [DOI: 10.1115/1.4034487]

1 Introduction

Analytical and experimental studies have proven that radially rotating (RR) heat pipes have an incredibly high effective thermal conductance and an enormous heat transfer capability. However, although the concept of the high-temperature radially rotating heat pipes has been validated through a series of experimental and analytical studies in the past, the studies so far are limited to individual heat pipes only. Additionally, none of the studies has improved the manufacturability and ability to implement sufficiently large volumes of heat pipes into a single device or structure effectively. Implementation of current heat pipe technology requires each one to be fabricated and employed individually into the device or structure, which may make heat pipe incorporation impractical and expensive for turbomachinery cooling applications.

It has been demonstrated that integrating heat pipes into turbomachinery would allow the material to withstand greater heat fluxes, hence allowing for increased efficiency. For practical industrial applications, individual heat pipes may need to be interconnected through a reservoir either at the bottom or at the top. For transition from the concept to industrial applications, a systematic study of the interconnected heat pipe systems should be undertaken. Having recognized the importance of the study, Cao and Ling have conducted a preliminary experimental study on an interconnected heat pipe system with a reservoir at the bottom. However, the preliminary study was largely unsuccessful. The heat pipes once interconnected were not functioning as expected, and subsequently the heat transfer enhancement was insignificant. It is therefore the objective of this research to design, fabricate, and test an interconnected heat pipe system with a reservoir at the top for turbomachinery disk cooling and to demonstrate the concept of the interconnected rotating heat pipe system. As a first step to validate the system, water was chosen as the working fluid instead of a high-temperature working fluid such as sodium.

As mentioned before, the purpose of this study is to develop a heat pipe system that could be cost effectively implemented into a turbomachinery disk. Figure 1 shows such a disk integrating a heat pipe system. As shown in the figure, the heat pipe system comprises a number of heat pipe branches that are interconnected through a common reservoir as the evaporator section of the heat pipe system. To minimize the costs of the experiment and due to symmetric structures around the circumference of the disk, only a section of the disk as defined by the two planes including four heat pipe branches needs to be studied and is depicted in the figure. This section is referred to as a sector heat pipe that incorporates four heat pipes (branches) and a common reservoir at the top, which is the focus of the present study.

2 Experimental Setup

2.1 High-Speed Rotating Test Apparatus. A high-speed rotating test apparatus was custom built specifically for testing rotating heat pipes [1–3]. It consists of a 1-hp motor, two slip rings, an attachment hub (consisting of an inner and outer cylinder), a support frame, and a safety enclosure. The revolution range of the rotating test apparatus is adjustable from 0 to 3600 revolutions per minute (rpm) and is controlled by an AC inverter. The two slip ring assemblies are mounted to the drive shaft and used to supply electrical power to the heater and to connect the thermocouples on the heat pipe to the data acquisition device (DAQ). The electric heater used to heat the heat pipes is adjusted by a transformer capable of delivering between 0 and 120 V, which is supplied by a two-channel slip ring. The lengthwise temperature distributions of the heat pipes were measured by five type K thermocouples connected to a National Instruments Compact Rio DAQ through the five-channel slip ring. Collection of the data was handled by a program written in LABVIEW for the DAQ.

2.2 Sector Heat Pipe With Interconnected Branches and Reservoir. The sector heat pipe with interconnected branches was fabricated from multipurpose copper (alloy 110) and filled with distilled water. A multipurpose copper (alloy 110) shell with distilled water as the working fluid was chosen due to the well-documented compatibility found in the literature [4]. The sector heat pipe was designed to operate at a vapor temperature of approximately 150 °C in the experiment. The sector consisted of four single heat pipes, each with a diameter of 3 mm and a length of 85 mm, as shown in Fig. 1. The four single heat pipes were

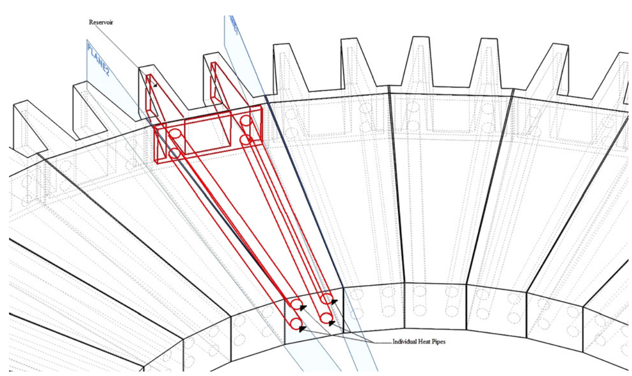

Fig. 1 Hidden line view of turbomachinery disk representation

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connected with a common reservoir, located at the top of the evaporator section, as shown in the same figure. For the purpose of fabrication, the sector had to be divided into two sections: the dovetail section containing the reservoir that serves as the evaporator section of the sector heat pipe, and a body section containing the four heat pipes' legs that serves as the condenser section of the sector heat pipe. A screw threading was machined as part of the body section in order to attach the sector heat pipe onto the outer cylinder of the high-speed rotating test apparatus. The dovetail cap (the evaporator section) was welded to the top end of the body of the condenser section, and a filling tube with an outer diameter of 2.0 mm was welded into the side of the sector near the top of the condenser section (Fig. 2). All of the heat pipe components were carefully fitted and cleaned according to standardized procedures. The welding process of the body, the evaporator dovetail cap, and the fill tube was conducted using rosin-soldering flux in order to prevent oxidation during the welding.

The sector heat pipe was charged with distilled water in Florida International University's Thermal Sciences Lab, and the filling procedure is outlined below:

1. The unsealed end of the heat pipe filling tube was attached to a vacuum pump.
2. While being pumped to a vacuum condition, the heat pipe was heated to $100-200\,^{\circ}\mathrm{C}$, in order to remove any absorbed water and gases.
3. When a level of high vacuum was obtained, the tube leading to the vacuum pump was pinched off.
4. An amount of distilled water was administered into the heat pipe using a syringe.
5. The filling tube of the heat pipe was pinched and welded, while the heat pipe was being maintained at a level of high vacuum.

The sector heat pipe with interconnected branches was charged with approximately 0.7 mL of distilled water, which is approximately the entire volume of the reservoir. Five type K thermocouples were used to measure the lengthwise heat pipe temperature distributions, and the thermocouples were calibrated by Omega Engineering Inc. to an accuracy of $\pm 0.5\,^{\circ}\mathrm{C}$. Two of the thermocouples were mounted at the dovetail section in order to measure the temperatures of the evaporator section, while the other three thermocouples were mounted along the condenser section to measure the lengthwise temperatures of the condenser section.

The heater for the heat pipe evaporator was constructed using resistance-heating wire of NI80-010 or NI80-012 of a nickel-chromium alloy, which was coated with a high-temperature chemical set cement, OmegaBond "600," for the purpose of electric insulation and minimizing contact thermal resistance between the evaporator and the heater wires. Both the resistance-heating wire and the cement were purchased from Omega Engineering Inc.

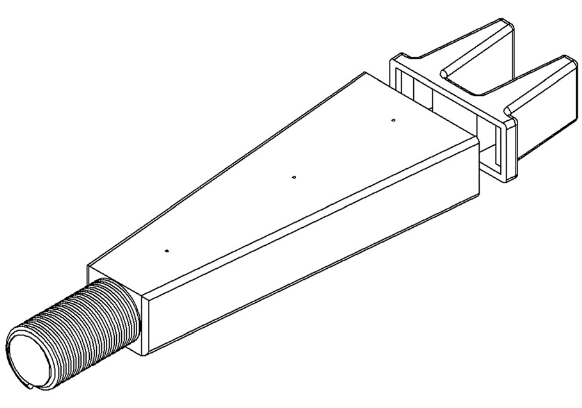

Fig. 2 Schematic of sector heat pipe, reservoir location

Once the heater was securely mounted to the dovetail section of the heat pipe, layers of wet-and-stick fiberglass insulation, approximately 16 mm thick, were wrapped around the heater to eliminate the heat loss from the heater to the ambient.

3 Error Analysis for Experimental Measurements

An error analysis is conducted in this section, and various potential sources for uncertainties are identified:

(1) Errors may be related to the experimental apparatus, specifically, the interference created by the vibrations of the experimental apparatus. Ideally, because the flow passages in a single radially rotating heat pipe are very small, the heat transfer and flow could approach one-dimensional conditions. However, during the heat pipe testing, as the frequency of rotation is increased, relatively large vibrations in the experimental apparatus are produced. This may create interruptions to the flow and heat transfer characteristics.
(2) Errors may also arise from the uncertainties in the heat input. The Fluke 80i-110 s, used to measure the current of the heater, has an uncertainty of less than 3% of reading $\pm$ 50 mA. In addition, the National Instruments NI-9219 module, used to measure the voltage readings from the current meter and the power supply of the heater, has an uncertainty of $\pm$ 0.3%. For a total uncertainty of heat input of approximately 3.6%.
(3) The uncertainties associated with temperature measurement are estimated as follows:

- type K thermocouples, which have an uncertainty of 0.5%.
- slip ring, used to connect to the thermocouples, has an uncertainty of 0.5%.
- high-temperature cement is used to attach the thermocouples. Errors could arise from the contact thermal resistance and can be assumed to be 1%.
- National Instruments NI-9213 module, used to measure the thermocouple readings, has an uncertainty of 0.03%.
- Milwaukee 2277-20 Laser Temperature gun, used to measure the surface temperature of the evaporator insulation, has an uncertainty of 1.5%.

Therefore, the total maximum uncertainty for the temperature measurement of the sector heat pipe is approximately 3.53%.

4 Experimental Results and Operating Characteristics

4.1 Test Results. Prior research has shown that there are a number of parameters that could influence the operation of radially rotating heat pipes [1–3,5–21]. The major parameters are the heat pipe size, dimensionless centripetal forces, heat input to the evaporator section, and noncondensable gases in the heat pipe. Since the primary objective of this study is to demonstrate the feasibility of a heat pipe sector with interconnected heat pipe branches and reservoir, both the manufactured sector heat pipe and the sector heat pipe shell (the heat pipe shell is the same heat pipe without any working fluid) are tested under the same working conditions. Figure 3 and Table 1 are the comparisons of the lengthwise temperature distributions of the sector heat pipe and the sector heat pipe shell at a heat input to the evaporator of 75 W and a rotating speed of 15 Hz.

From Fig. 3 and Table 1, it is clear that the heat transfer capacity of the heat pipe shell is very low, which is only 75 W. Further increase in the heat input to the heat pipe shell will result in an exceptionally high temperature beyond the test range of the experimental study. The lengthwise temperature distribution for the shell is approximately linear, and the temperature at the condenser end is nearly that of the ambient temperature, typical of a

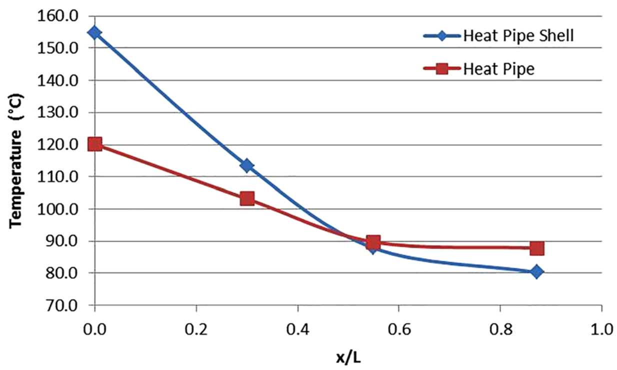

Fig. 3 Temperature distributions of sector heat pipe and sector heat pipe shell ($Q = 75$ W and $f = 15$ Hz)

Table 1 Comparison of sector heat pipe and sector heat pipe shell ($Q = 75$ W and $f = 15$ Hz)

Dimensionless heat pipe length (x/L)	Temperature distribution for heat pipe (°C)	Temperature distribution for heat pipe shell (75 W) (°C)
0.0	120.1	154.7
0.30	103.1	113.4
0.50	89.8	87.9
0.90	87.8	80.3

heat conduction mode. For the sector heat pipe with the same dimensionless centripetal force and geometrical dimensions, significantly more heat can be transferred. At a heat input of 75 W, the maximum temperature of the heat pipe sector is still much lower than the maximum temperature allowable, indicating that the sector heat pipe is working. The lengthwise temperature distributions of the evaporator section and the majority of the condenser section are nearly uniform. It is apparent that the heat pipe works flawlessly in these sections; nonetheless, there occurs a large temperature gradient near the end of the condenser. This is most likely due to the condenser end being affixed to the outer cylinder of the high-speed rotating test apparatus with a screw thread, which creates a heat sink at the condenser end and allows for more heat from the condenser end to be transferred into the outer cylinder. Consequently, because of the heat transferred to the outer cylinder at the condenser end, the temperature distribution near the condenser end is lowered.

The steady-state operation of the sector heat pipe, with a rotational speed of 45 Hz at different heat inputs, is illustrated in Fig. 4. From Fig. 4, it is evident that the evaporator section of the sector heat pipe begins to work when the heat input reaches 35 W. By increasing the heat input, the operating temperature in the evaporator section will increase, causing the vapor flow rate to increase accordingly. Concurrently, the working section in the condenser will be prolonged to the condenser end, causing the lengthwise temperatures of the condenser section to increase rapidly. Nonetheless, the temperature gradient proximate to the end of the condenser section continues to remains large due to the heat sink formed from the outer cylinder. Considering the high conductivity of the shell (copper), this lowered temperature near the condenser end is understandable.

At higher rotational frequencies (higher rotating speeds), the dimensionless centripetal force becomes an important factor for the lengthwise temperature gradient of the heat pipe. If geometrical dimensions of the heat pipe and the heat input are fixed, as the rotating speed is increased, the lengthwise temperature gradient and pressure drop of the heat pipe will increase. This occurs because as the rotating speed is increased, the heat transfer coefficient associated with the air-cooling at the outer surface of the heat pipe sector in the condenser section will increase, which reduces the condenser temperature and increases the temperature gradient along the hat pipe, as shown in Fig. 5. It should be pointed out that at a higher rotating speed the film thickness of condensate inside the heat pipe sector will decrease. Accordingly, the heat transfer at the inner surface of the condenser will be improved. If the cooling airflow rate outside of the condenser could be maintained at a constant value without causing the condenser temperature reduction, the temperature gradient along the heat pipe length could even be reduced at a higher rotating speed due to the improved performance inside the heat pipe sector. Unfortunately, the cooling airflow rate control mechanism is absent in the present study.

The heat pipe fill ratio is defined as the water filling volume divided by the volume of the reservoir. Proper fill volume in heat pipes is essential to operational effectiveness. When a heat pipe does not have a proper fill volume, two issues may occur: the dry-out limitation can be reached for too little working fluid, or heat pipe flooding due to too much working fluid in the heat pipe. The dry-out limitation can be reached when the fill volume of the working fluid is very small that could only sustain a comparatively small radial evaporator heat flux. With this scenario, although the film of condensate could continue to return to the evaporator section, the liquid film thickness may approach zero at the top of the evaporator section. Consequently, the entire amount of working fluid may be distributed throughout the heat pipe branches without enough liquid left in the evaporator reservoir. Increasing the heat input in the evaporator section will initiate dry-out in the top of the heat pipe. The size of the dry area will continue to enlarge with increasing heat input. Subsequently, the wall temperature increases progressively, due to evaporation not occurring in the dry area. This phenomenon is illustrated in Fig. 6 for a fill ratio less than 50%. In addition, it can be seen from these

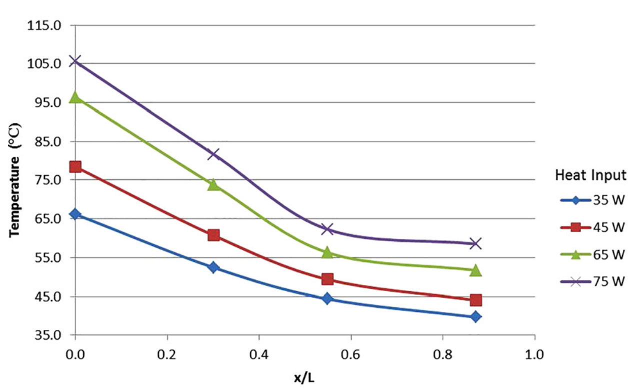

Fig. 4 Lengthwise temperature distributions of the sector heat pipe with different heat inputs ($f = 45$ Hz)

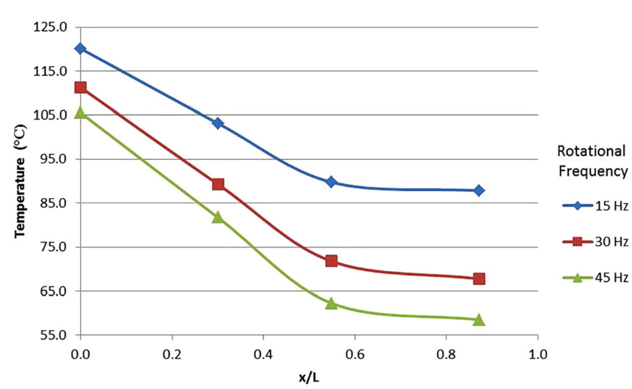

Fig. 5 Lengthwise temperature distributions for sector heat pipe with different rotational frequencies ($Q = 75$ W)

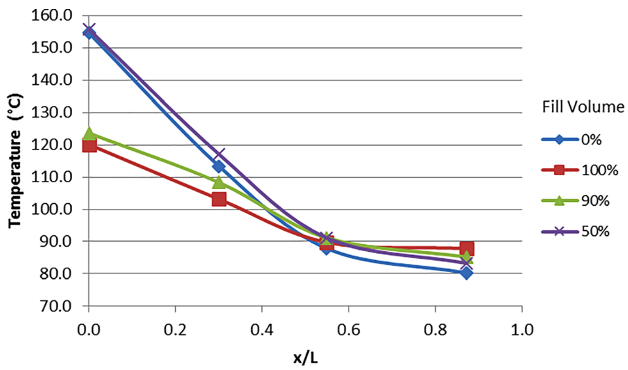

Fig. 6 Lengthwise temperature distributions for sector heat pipe with different filling ratios ($Q = 75$ W and $f = 15$ Hz)

figures that a 100% fill volume (the reservoir is mostly filled with liquid) provides the best performance of the heat pipe sector.

5 Conclusions

Extensive experimental tests on a new sector heat pipe have been conducted with distinctive parameters varied. Conferring to the experimental and analytical studies performed, the following conclusions can be made:

(1) Multiple radially rotating heat pipes can be integrated into a turbomachinery device, such as a disk, and connected with a common reservoir. Considering its simple structure, lower manufacturing costs, ability to withstand strong vibrations, high effective thermal conductance, and high heat transfer capacity, the radially rotating heat pipe is feasible for integration into large and complex rotating structures for cooling purposes.

(2) The heat transfer characteristics and lengthwise temperature distribution of the heat pipe are influenced by the heat input, centripetal force, and inner diameter of the heat pipe. Additionally, the fill ratio has a significant effect on the performance of the sector heat pipe.

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Nomenclature

A = cross-sectional area, m^2
d = heat pipe diameter, m
f = rotating frequency, Hz
g = gravitational acceleration, m/s^2
h_c = heat transfer coefficient, $W/m^2\,K$
h_{fg} = latent heat of vaporization, J/kg
k = thermal conductivity, W/m K
k_p = thermal conductivity of heat pipe wall, W/m K
L = length of the heat pipe, m
Q = heat transfer rate, W
q^n = heat flux, W/m^2
R, r = heat pipe radius, m
T = temperature, K or °C

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