Heat transfer in a centrifugal vortex tube

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Abstract. The results of an experimental study of the heat flux in a model of a centrifugal vortex apparatus with a lower rotating disk are presented. An experiment considered three cases at a distance between the disks $H = R/2$ and $H = R$: "water", "water-air", and "water-oil". Using the colorimetric method, the dependence of the heat flux on Reynolds is shown. The case "water-air" was chosen to evaluate the contribution to heat exchange from the thermocapillary effect (Marangoni) at high Re. For the case of two immiscible liquids of different densities (water-oil), the effect of "centrifugal levitation" is found.

1. Introduction

Centrifugal heat pipes (CHPs) are one of the varieties of closed evaporation and condensation devices used for cooling and heating the rotating machine parts. The main difference between CHP and traditional loop heat pipes (LHP) is that the return of the working fluid from the cooling zone to the heating zone is carried out under the action of centrifugal forces. In this case, the processes of heat and mass transfer proceed much more intensively than in conventional LHP. The field of centrifugal forces enhances natural convection, which leads to an increase in the heat transfer coefficients from the evaporator wall to the working fluid [1].

The novelty of our approach is that the circulation of the working fluid in the CHP is created by the rotation of the end cold disk. The work studies the influence of the modes of simultaneous vortex and circulation motion of (a) water, (b) water-air, and (c) water-oil systems on heat transfer. This is important for the prospects of creating new centrifugal heat pipes and intensifying the heat exchange process [2]. The main difference between our CHP and traditional rotating cylindrical heat pipes [3, 4] is that in our case, the convection of the working fluid is not free, but forced. At that, in the case of two immiscible media, at small swirls of the cold disk, the vortex motion of the liquid adjacent to the cold disk forms the circulation motion of the second liquid adjacent to the hot surface, as it was studied in detail in [5-7] for the isothermal case.

2. Problem Formulation

The laboratory model of CHP consists of the basis with the mounted plexiglass pipe, being a cylinder with an inner radius $R = 47.5$ mm and a height $L = 200$ mm, which performs the role of the adiabatic wall (figure 1).

In the upper part of the unit there is a fixed copper disk with a soldered heat-exchange copper tube with hot coolant (water). The heat supply is implemented using a liquid circulation thermostat WCB-6 WITEG (DAIHAN). The temperature of the "hot" coolant at the entrance of the CHP is set to $+60^\circ$C.
The cold heat carrier (water) flows through a heat-exchange copper tube. Heat is removed by cold water supply: a circulation pump and an external water tank. The temperature of the "cold" coolant at the inlet is maintained at +23°C. The flow rate of “hot” and “cold” coolants is 1.5 l/min.

The flow rate of the coolant is measured by a flow meter with a pulse output, and the temperature at the inlet and outlet of the heat-exchange tube is controlled by Tsic 506 thermal sensors with an accuracy of ±0.1°C.

The generation of the vortex motion of the working fluid is provided by the rotation of the bottom, i.e. a copper disk, which is driven by a stepper motor. The stepper motor ensures a rotation frequency of the copper disk ω in the range from 0 to 31.4 radians per second. The Reynolds number is determined by the formula: \( Re = R^2 \omega / s \), where R is the radius of the pipe, \( \omega \) is the angular frequency of rotation of the lower disk, and \( v \) is the kinematic viscosity of water at the periphery of the lower disk, which is "threaded" in the program as a polynomial of viscosity dependence on temperature. The water temperature is measured by a sensor \( T_w \) located on the wall near the lower disk. Thus, for a given Reynolds number, the sought parameter is the angular frequency of the disk rotation, which is a feedback parameter and is set by a sound generator controlled from a PC. The disk rotation parameters are controlled, and the parameters from temperature sensors and flow meters are measured and recorded via the Arduino board in the developed software.

The calculation of the heat flux from the hot disk to the adjacent working fluid is determined by the heat balance:

\[
W = c \rho Q (T_{in} - T_{out})
\]

where \( c \) and \( \rho \) are the heat capacity (4180 J/(kg*K)) and the density (1000 kg/m³) of the coolant (tap water), \( Q \) is the volume flow of the coolant, and \( T_{in} \) and \( T_{out} \) are the temperatures at the inlet and outlet of the heat-exchange tube adjacent to the disk. A similar formula is used to determine the heat
flux at the cold lower disk. For applications, the heat flux at the hot disk is more important, and an additional measurement at the lower disk allows estimating how much heat outgoes through the side wall of the cylinder. The nondimensional heat flux is determined by the formula:

\[ W^* = \frac{W}{W_0} = \frac{q_w}{q_{\alpha}} = \frac{\alpha \Delta T S}{\lambda S l} \]

(2)

where \( W_0 \) is the heat flux at rest (at \( Re=0 \)), i.e., only due to thermal conductivity \( Q_\lambda \), and \( W \) is the forced convection heat transfer, i.e., only rotation \( Q_c \), \( \alpha \) is heat transfer coefficient, \( l \) is characteristic size and \( \lambda \) is coefficient of thermal conductivity of the coolant. The ratio of these values corresponds to the Nusselt number. The Nusselt number for the process of convective heat transfer with the forced motion of the coolant is:

\[ Nu = \frac{\alpha d}{\lambda} = f(Re Pr) \]

(3)

The Prandl number characterizes the physical properties of the coolant. The measurement accuracy is ± 0.1° C for temperature and 5% for liquid flow rate. The error values are shown in the graphs.

3. Discussion of experimental results
The experiments were carried out in the CHP model at a distance between the disks \( H=R/2 \) and \( H=R \). Distilled water and a combination of water-air and water-vegetable oil at a volume ratio of 50 to 50 was used as the working fluid.

Distilled water was poured into the heat pipe, heating was turned on and rotation was created at \( Re=6000 \). After the thermostat reached the stationary mode (+60° C), a pump supplying "cold" coolant from the tank was turned on. The setup remained in this state for 2-3 hours, after which the air (previously dissolved in water) was removed from under the upper disk. Then the pump was turned on, feeding the "cold" coolant from the tank, and the rotation of the disk stopped. After the equilibrium was established, the experiment started. The first measurements were made without rotating the disk. After an exposure of 600 seconds, an increase in the Reynolds number occurred and then a subsequent exposure of 600 seconds took place.

Figure 2 shows the dependence \( W^* (Re) \) only for water and water-air with equal volumes. In the case when the container was filled only with water, with an increase in \( Re \) from zero to 20000, the heat flux increased rapidly, and then became almost constant: about \( W^*=10 \pm 0.48 \) at \( H = 0.5 \ R \) and about \( W^*=8 \pm 0.46 \) at \( H=R \). Therefore, to improve heat transfer in this case, it was sufficient to limit the rotation speed to \( Re \) of about 20000-30000 in order to avoid inefficient energy costs.
The case when the container was filled with water and air was chosen to evaluate the contribution to heat exchange from the thermocapillary effect (Marangoni) at high $Re$, when the water-air interface became almost vertical. The surface tension decreased with increasing temperature and, therefore, a tangential stress appeared on the surface, pushing the adjacent water from the hot disk to the cold one. This enhanced the water circulation created by the rotating disk.

In comparison with water, air served almost as an insulator, preventing heat exchange. Therefore, with increasing Re, $W^*$ almost did not change, remaining close to 1 until water contacted the hot disk. Rapid rotation deformed the water surface, creating a funnel near the axis and a rise in the level at the wall, and at a certain Re, water contacted the upper disk [8, 9]. For $H = 0.5 \, R$, this happened at Re of about 18000, and for $H=R$, the contact of the stationary disk occurred at Re of about 50000. This difference is clear: to raise the water at the side wall to a height of 0.5 R, a faster rotation is required, as compared to a height of 0.25 R. It is shown that after the contact (with a further increase in Re), a rapid growth of $W^*$ occurs due to an increase in water velocity and the area of its contact with the hot disk. Then the area reaches its limit, and as a result, the growth of $W^*$ slows down, but continues up to $Re=90000$ (the largest possible on this experimental setup). This is different from the case with water only, and this difference is better expressed at $H=R$ (blackened characters in figure 2) about $W^*=18 \pm 0.63$ at $H = 0.5 \, R$ and about $W^*=22 \pm 0.69$ at $H=R$. In the case of water only, $W^*$ almost does not change at Re over 30000, unlike in the water-air system. It may be assumed that the continued growth of $W^*$ is associated with the Marangoni effect.

In the "water-oil" experiment (figure 3), distilled water was poured into the heat pipe and vegetable oil was poured with a syringe without mixing. The heating of the coolant was turned on, and a rotation was created at $Re=2000$. The setup remained in this state for 20 minutes. Then the pump was turned on, feeding the "cold" coolant from the tank, and the rotation of the disk stopped. After the equilibrium was established, the experiment started. The first point in the experiment was without rotation of the disk. After an exposure of 1200 seconds, an increase in the Reynolds number and a subsequent exposure of 1200 seconds occurred. Additionally, visualization was carried out using a digital camera.

![Figure 2. Dependence $W^*(Re)$ only for water (squares) and water-air with equal volumes (triangles) at $H=0.5R$ (not filled) and $H=R$ (filled).](image-url)
In the speed of disk rotation, the heat output remained at a constant level until the oil funnel contacted the rotating disk (oil adheres to the disk). Thus, it may be concluded that regardless of the speed of circulation of both water and oil, there was actually no heat exchange between these two media, or at least it was not intensified. At the Reynolds numbers of 6000 and 8000, respectively, the upper liquid contacted and adhered to the lower rotating disk, which resulted in an increase in heat exchange. After the funnel contacted the oil, there was a jump in the output power, which then gradually increased until the oil started circulating throughout the entire cylinder volume, enclosing a segment of water in a torus that contacted neither the upper nor the lower disk.

Further, there was an increase in the Reynolds number to 10,000 – the liquid turned into an emulsion and began to circulate throughout the volume – and then, the plateau was achieved as for the case of mono-fluid (water). The thermal conductivity of the oil-water emulsion was much less than that of water, so the values of the output power were 3-4 times less than for water about $W^* = 15 \pm 0.52$ at $H = 0.5 \ R$ and about $W^* = 6 \pm 0.53$ at $H=R$.

Experiments with immiscible liquids in the water-oil system have revealed a curious and impressive stable phenomenon, which may be called “centrifugal levitation” (figure 4). As the rotation increased, the liquid interface deformed, forming a funnel typical of an eddy, but in this case filled with oil. Then the oil reached the rotating disk, spread along the bottom to the side wall, and rose along it to the very top, locking the lower liquid in a thin layer. Thus, water took the form of a torus that contacted neither the walls nor the axis of the container, that is, “levitated” in the oil. At the same time, the flow was unstable: both axial and circumferential fluctuations and curvatures of the torus with water were observed. This “levitation” is forced and is due to centrifugal force, in contrast to levitation based on the Leidenfrost effect [8, 9]. The oil created a thin film on the lower disc and side walls of the heat pipe, which prevented heat transfer by analogy with the Leidenfrost effect observed in [8,9].

![Figure 3](image.jpg)
4. Conclusions
The dependence of the heat flux on the Reynolds number has been studied in the model of a centrifugal vortex apparatus with a lower rotating disk in the water, water-air and water-oil system. It is shown that the heat flux in the water-air system continues to increase at large Reynolds numbers, and this increase is most likely associated with the Marangoni effect. For the case of water-oil, it is shown that with an increase in the speed of disk rotation, the heat output remains at a constant level until the oil funnel contacts the rotating disk, confirming the conclusion that there is no heat exchange between these two media, regardless of the speed of circulation of both water and oil. With a further increase in the Reynolds number, a transition to an emulsion occurs, which behaves like the case of "water" only with lower thermal conductivity. The phenomenon of "centrifugal levitation" is detected at the motion of two immiscible liquids, while the oil begins to circulate throughout the entire volume of the cylinder, enclosing a segment of water in a torus that contacts neither the upper nor the lower disk.

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