HEAT-TRANSFER ANALYSIS OF A WATER-COOLED CHANNEL FOR THE TPS FRONT-END COMPONENTS

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Abstract

The masks, absorbers and slits must withstand the extremely high power and power density in the TPS front end. The material always used is OFHC or Glidcop. One solution is to increase the cooling efficiency of the water-cooled channel in these components. With the restrictions of water pressure < 7 kg/cm^2 and water flow velocity < 3 m/s, the wire coil is chosen to enhance the average heat-transfer coefficient and increase not too much the loss of water pressure. With a water channel of diameter 7.5 mm and wire coil inserts of pitch 7.5 mm and wire diameter 1 mm, the cooling efficiency becomes enhanced 1.4 to 2 times in the components of the TPS front end. The wire coils of varied pitches are simulated and calculated in this work. We also compare our investigated data with other experimental data of other authors.

INTRODUCTION

TPS is a third-generation synchrotron radiation facility. The electron beam stored in the storage ring, of circumference 518 m, has energy 3 GeV and current 500 mA. An insertion device (ID), installed in the straight section, emits much power of synchrotron radiation to the front end. For example, IU22 of ID has power density 65 kW/mrad^2 and total power 9.7 kW. Parts of the straight sections have two ID, doubling the power. The large heat-load components as masks, absorbers and slits are responsible to absorb the heat load of the high power density and the large total power in the front end.

Two methods are adopted to design these high heat-load components: one is the use of a small angle of grazing incidence to decrease the power density; the other is a water channel with enhanced heat transfer. In practice, the angle of grazing incidence is between 1 -- 2^o. To prevent the vibration induced by water flow, the velocity of that flow is constrained < 3 m/s. To protect the components on the water piping, the water pressure in the water source of utility is 7 kg/cm^2. As the water velocity and water source pressure are constrained, we need to use wire coil inserts to enhance the heat transfer.

Many researchers [1~3] have presented results for enhanced heat transfer from experimental methods used in a synchrotron radiation facility. Wire coil inserts are a popular method to enhance heat transfer within water channels.

The water channels in these components of high heat load at the TPS front end have 8 water channels with two input tubes and two output tubes. The input and output tubes have diameter 0.5 inch, so the 8 water channels are designed to be 7.5 mm to match the water flow rate. We analyzed the 7.5-mm water channel with varied pitch of wire coil inserts by using an equation and a commercial program (Solidworks Flow Simulation).

SMOOTH CHANNEL

The heat-transfer coefficient h for a smooth channel is obtained from

$$h = Nu\, k_f/D_h \quad (1)$$

in which Nu = Nusselt number, k_f = thermal conductivity of water and D_h = hydraulic diameter. The Nusselt number is calculated with the Dittus-Boelter equation,

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad (2)$$

in which Re = Reynolds number, Pr = Prandtl number.

The pressure loss dP for a smooth channel is obtained from the Darcy-Weisbach equation,

$$dP = f\ (L/D_h)\ (\rho\ v^2/2) \quad (3)$$

in which f = Darcy-Weisbach friction coefficient, L = length of channel, ρ = density and v = velocity.

Considering water velocity < 3 m/s, water pressure < 7 kg/cm^2 and the pressure loss effect, we calculate the water flow rate from 3 to 6 L/min shown in Fig. 1.

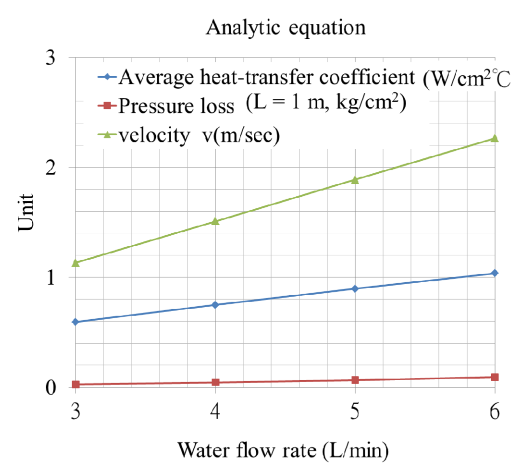

Figure 1: Average heat-transfer coefficient, pressure loss and velocity of a smooth water channel of diameter 7.5 mm.

An average heat-transfer coefficient larger than 1.5 W/cm^2 has no significant impact on decreasing the solid temperature and the drawback of increasing the pressure loss [1~3]. Figure 1 shows that the average heat-transfer coefficient can be only 1 W/cm^2 °C. The reasonable range of average heat-transfer coefficient is from 1 to 1.5 W/cm^2 °C. On using wire coil inserts, the average heat-transfer coefficient can be increased to 1.5 W/cm^2 °C.

WIRE COIL INSERTS

The water-cooling loops of the component with a large heat load are all formed of the same method: each component has two water loops; each loop has four water channels with one water-in tube and one water-out tube, as shown in Fig. 2, a sketch of a helical wire coil inserted in a smooth channel, of inner diameter *d*, with pitch *p* of helical wire, and wire diameter *e*.

The heat transfer is affected by dimensionless parameters *e*/*d* and *p*/*d*, but the wire diameter makes only a slight influence. The pressure loss depends mainly on dimensionless parameters *p*/*d* [4]. We can therefore fix the wire diameter as 1 mm and vary the pitch as 6, 8, 10 and 12.7 mm to observe the variation of pressure loss and average heat-transfer coefficient.

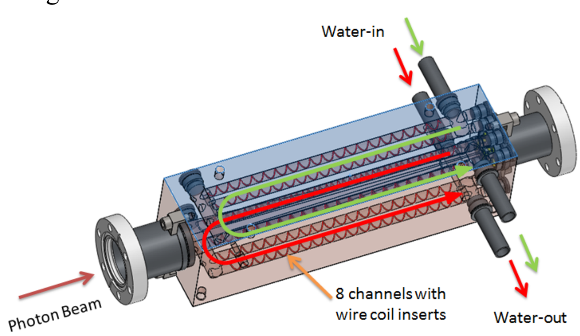

Figure 2: Water loops of a component with a large heat load.

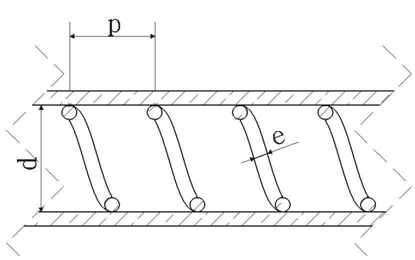

Figure 3: Sketch of a helical wire coil inserted in a smooth channel.

SIMULATION

The commercial program (SW Flow Simulation) served to simulate the pressure loss and average heat-transfer coefficient. The inner diameter of the water channel is 7.5 mm; the length of channel is 10 cm. The wire diameter is 1 mm; the minimum length in the simulation is set as 0.2 mm. The pitches of the helical wire are 6, 8, 10 and 12.7 mm. The wire coil is simulated with and without brazing of the inner channel.

RESULTS

A comparison of the average heat-transfer coefficient and pressure loss of a smooth tube are obtained with the equation and (SW Flow) simulation in Fig. 4. The maximum deviation is about 10 %.

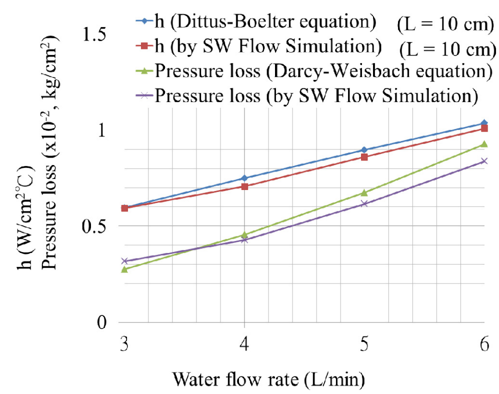

Figure 4: Data of a smooth tube from an equation and from (SW Flow) simulation.

The pressure loss of a wire coil of pitch 6 mm is almost twice that of a wire coil of pitch 12.7 mm, in Fig. 5. The average heat-transfer coefficient of a wire coil of pitch 6 mm is increased just about 10 % above that of a wire coil of pitch 12.7 mm, in Fig. 6. The pitch effect of the wire coil is more sensitive to the pressure loss than the average heat-transfer coefficient.

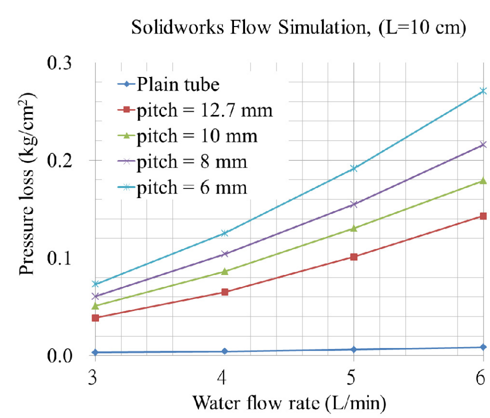

Figure 5: Simulation of pressure loss with varied pitch of helical wire.

Figure 6 shows that, without a wire coil brazed on the inner wall of the channel, the average heat-transfer coefficient is enhanced at least 1.4 times that of a plain tube. Figure 7 shows, with a wire coil brazed on the inner wall of the channel, the average heat-transfer coefficient is enhanced at least twice that of a plain tube. In practice, the wire coil inserted into the plain tube can be brazed with brazing material, but the brazing performance is uncertain. First, the wire coil might have a gap between the inner wall of the tube and the wire coil. Second, the brazing material is brazed in an environment of high temperature of a brazing furnace. For example, for the

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50Au/50Cu brazing material, the melting temperature is 970 °C. We cannot ensure that the brazing material filled well between the inner wall of the tube and the wire coil.

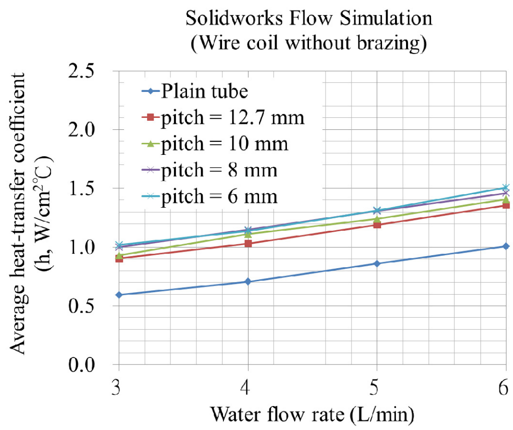

Figure 6: Simulation of average heat-transfer coefficient with varied pitch of wire, without brazing on the inner wall.

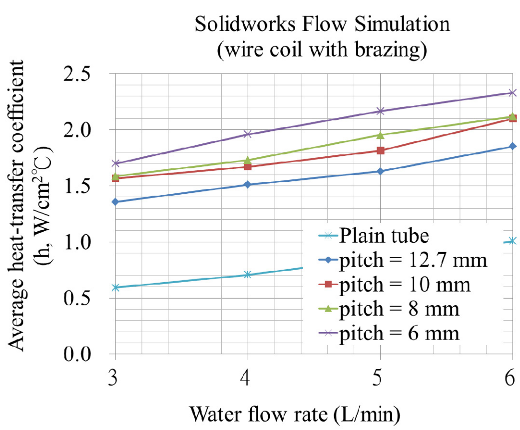

Figure 7: Simulation of average heat-transfer coefficient with varied pitch of wire, with brazing on the inner wall.

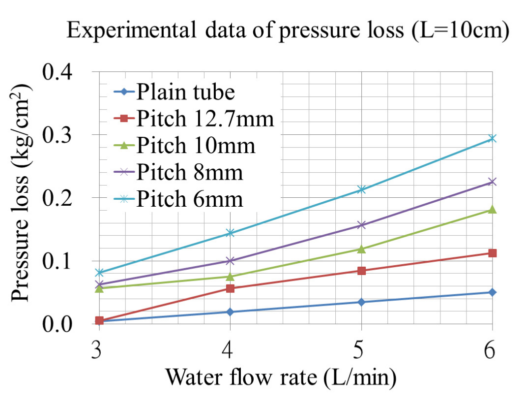

Figure 8: Experimental data of pressure loss.

The pressure loss obtained by experiment has a larger deviation than that calculated with an analytic equation or simulated (SW Flow Simulation), as shown in Fig. 8. The deviation of pressure loss can double between the experimental and analytic data.

Figure 9 shows the average heat-transfer coefficient calculated with fitting equation (4) in paper [4]. This fitting equation was obtained on fitting many experimental data of other researchers.

$$h = 0.132(p/d)^{-0.372} Re^{0.72} Pr^{0.37}\, k_f/D_h \qquad (4)$$

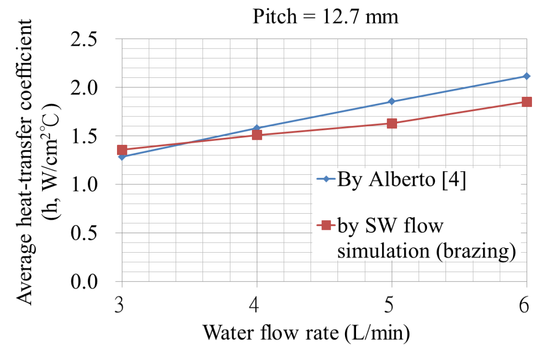

Figure 9: Comparing the average heat-transfer coefficient of equation (4) data with simulation data.

CONCLUSION

Many researchers have reported experimental data for the average heat-transfer coefficient and pressure loss. Among this research, the experimental data have almost twice the difference [4].

In other research, a wire coil inserted into the tube has an enhancement effect over that of a plain tube about twice, depending on the water flow rate and dimensionless parameters e/d and p/d [1-4].

In the constrained condition of water velocity < 3 m/s and water pressure < 7 kg/cm^2, the design specification of average heat-transfer coefficient is suitable to be 1 W/cm^2 °C. In a water channel of diameter 7.5 mm, inserting a wire coil with d = 1 mm and pitch = 12.7, we increase the average heat-transfer coefficient from 1 to 1.5 W/cm^2 °C used in the TPS front end.

ACKNOWLEDGMENT

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