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Experimental Method for Flow Calibration of the Aircraft Liquid Cooling System

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Abstract: In the process of aircraft operation, the flow calibration of aircraft liquid cooling system has always been one of the research hotspots in engineering. Based on the principle of the differential pressure method, a new experimental flow calibration method is proposed for the aircraft liquid cooling system in this paper. In the reducer and the square bend of the aircraft liquid cooling system, the pressure difference will be generated. The flowmeter is used to measure the flow of the coolant, and the flow rate coefficient of the aircraft liquid cooling system can be calibrated. The experimental platform is established to conduct the flow calibration of the aircraft liquid cooling system, and the influence of the temperature and imported pressure on the flow will be investigated. Results indicate that the experimental method proposed is very effective, and the flow calibration can be realized without damaging the aircraft liquid cooling system.

Keywords: liquid cooling system; flow calibration; differential pressure; experimental method; aircraft

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1. Introduction

With generous applications of the avionics and the continuous improvement of the radar power, the air cooling system cannot fully satisfy the cooling requirements, and the liquid cooling system emerges as the times requires. Compared with the air-cooling system, the liquid cooling system has several advantages, such as the larger refrigeration capacity, the simpler system design, the secondary cooling with fuel or punching air, and no influence on the normal work of the aircraft. At the same time, the heat transfer coefficient [1,2] and specific heat of the liquid are much greater than the air, and the liquid cooling system has higher cooling efficiency and stable working ability. Therefore, the liquid cooling system for high-performance aircraft electronic equipment has become an inevitable trend.

Under normal conditions, the main characteristic parameters of the liquid cooling system are the temperature and pressure. In order to evaluate the cooling performance of the liquid cooling system more accurately, the flow of the coolant becomes another important parameter, which can be obtained through the experimental measurement. Around the 21st Century, many liquid flow measurement methods had been proposed [3–7], but there are several disadvantages among these methods proposed, such as the leakage, restriction of the flight condition, the toxic of the refrigerant and so on, which were very difficult to be applied to the liquid cooling system of the aircraft. Therefore, it is necessary to find a safe and feasible flow measurement method for the aircraft liquid cooling system.

In recent years, the aircraft liquid cooling system has become an important development direction of the aircraft refrigeration system, and researches on domestic aircraft liquid cooling system have just started. Zheng et al. [8] used the experimental method to calculate the flow correction coefficient. Tian et al. [9] introduced the usage, the characteristics and the application scope of common flow counters in industry briefly. Ahrens et al. [10] used a telecentric CCD imaging system to track a moving liquid meniscus inside a glass capillary, and developed a new experimental setup for measuring ultra-low flows. Doihara et al. [11] developed a calibration rig, which consisted of a syringe pump and a weighing tank system, to conduct the flow calibration in the flow range of Ma et al. [12] considered the diversion damper situation and the jet flow velocity profile, and developed a measurement error model of diverter to overcome the error calculation difficulties of the diverter in the liquid flow calibration facilities. Nakada et al. [13] constructed a flow measurement system consisting of an acoustic emission sensor and a signal processing circuit, and transformed the acoustic emission signals into the corresponding flow. Restricted by the limited space of the aircraft cabin, some liquid flow measurement equipment commonly used are difficult to implement modification on the aircraft, which can cause many safety problems, such as the leakage of the coolant and the performance of the system. Therefore, these flow measurement methods above are difficult to carry out on the aircraft.

To overcome this problem, a new flow measuring method of the aircraft liquid cooling system is proposed in this paper. This method does not need to modify the liquid cooling system, so it will not affect the normal work of the aircraft liquid cooling system. According to the principle of the differential pressure method, the experimental platform of the aircraft liquid cooling system is established, and the flow calibration is carried out based on the pressure difference of the reducer and the square bend. Experimental results indicate: the flow calibration method proposed is correct and effective, which can be applied to the flow measurement of the aircraft liquid cooling system.

2. Flow Rate Calibration Scheme

There are many flow measurement methods [14–16] proposed interiorly, such as the differential pressure flowmeter method, the volumetric flowmeter method, the float flowmeter method, the blade flowmeter method, the electromagnetic flowmeter method, the vortex flowmeter method and the ultrasonic flowmeter method. Most of these methods need special flowmeters. Many problems will be encountered during the installation of special flowmeters, interfering with the normal operation [17] and affecting the safety check of the liquid cooling system [18]. A variety of flow calibration methods have been proposed based on the physical properties of geometrical characteristics [19,20], and the most feasible method is the differential pressure flow measurement method.

The differential pressure flow measurement principle, is to fix a throttle with an area less than the section area of the pipe in the liquid filled pipe, and the liquid in the pipe will shrink when it passes through the throttle, then the flow velocity will increase and the static pressure will drop at the contraction; finally a certain pressure drop will generate before and after the throttle.

As shown in Figure 1, two cross-sections are taken on a variable diameter pipe, Sections 1 and 2. Section 1 is the cross-section before the contraction of the stream, and Section 2 is the cross-section after the contraction of the stream. According to the Bernoulli Equation of the incompressible ideal fluid and continuity equation of the incompressible fluid constant flow:

$$\frac{p_1{}'}{\rho_1} + \frac{u_1{}^2}{2} = \frac{p_2{}'}{\rho_2} + \frac{u_2{}'^2}{2} \tag{1}$$

$$A_1 u_1 = A_2 u_2 \tag{2}$$

where: $p_1{}'$ and $p_2{}'$ are the average pressures of the fluid at Sections 1 and 2; ρ_1 and ρ_2 are the density of the fluid at Sections 1 and 2; u_1 and $u_2{}'$ are the flow velocities at Sections 1 and 2; A_1 and A_2 are the areas of Sections 1 and 2.

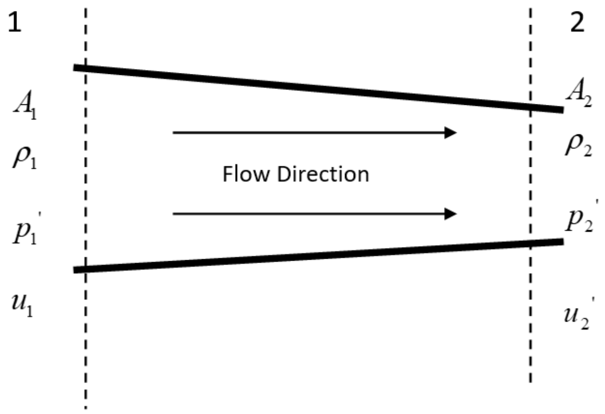

Figure 1. Diagrammatic sketch of a variable diameter pipe.

For the same coolant, $\rho_1 = \rho_2$. Substitute Equation (2) into Equation (1), and the flow velocity at Section 2 can be derived as follows:

$$u_2{}' = \frac{1}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2}{\rho}(p_1{}' - p_2{}')} \tag{3}$$

The flow velocity at Section 2 $u_2{}'$ can be rewritten as follows:

$$u_2{}' = \frac{1}{\sqrt{1-\mu^2\beta^4}}\sqrt{\frac{2}{\rho}(p_1{}' - p_2{}')} \tag{4}$$

where: μ is the contraction coefficient of the stream; β is the diameter ratio of the throttle device, and $\beta = \sqrt{A_2/A_1}$.

Because $p_1{}'$ and $p_2{}'$ are the average pressures of the fluid at Sections 1 and 2, the pressure drop $p_1 - p_2$ is read at the pipe wall according to a certain way of taking pressure in the actual measurement. Therefore, a pressure correction coefficient ψ needs to be introduced, and $p_1{}' - p_2{}' = \psi(p_1 - p_2)$. When the taking pressure method is different, the pressure correction coefficient ψ is different from coefficients of other pressure methods. In engineering practice, there is flow velocity loss in the fluid flow, which is different from the assumption of the isentropic constant flow. Therefore, a coefficient ξ is introduced to modify the flow velocity $u_2{}'$. The volume flow of the incompressible fluid after modification can be expressed as follows:

$$G = u_2\mu A_0 = \frac{\mu\xi\sqrt{\psi}}{\sqrt{1-\mu^2\beta^4}}A_0\sqrt{\frac{2}{\rho}(p_1 - p_2)} \tag{5}$$

where: $p_1 - p_2$ is the actual pressure drop measured.

The mass flow of the incompressible fluid [21] after modification can be expressed as follows:

$$G = u_2\mu A_0 = \frac{\mu\xi\sqrt{\psi}}{\sqrt{1-\mu^2\beta^4}}A_0\sqrt{2\rho(p_1 - p_2)} \tag{6}$$

where: G is the flow of coolant in the pipe.

Assume that a is the flow coefficient, and $a = \frac{\mu\xi\sqrt{\psi}}{\sqrt{1-\mu^2\beta^4}}$. The flow coefficient is related to the form of the throttle, the ratio of the diameter, the way of the pressure withdrawal, the Reynolds number of the flow and the roughness of the tube wall. Because μ, ξ and ψ cannot be measured directly, the flow rate coefficient is generally determined by the experiments.

3. Establishment of Experimental Platform

For the aircraft liquid cooling system, the flow measurement is really difficult. Firstly, the pipeline of the aircraft liquid cooling system cannot meet the length requirements of the straight pipe before and after the throttle; Secondly, the installation of the throttle device on the pipe can affect the flow resistance characteristics of the whole system, which can also increase the possibility of the leakage of the coolant.

In the technical index of a certain type of the aircraft liquid cooling system, the imported pressure of the radar components is 930 kPa, and the configuration of a throttle device may cause 50 kPa or even greater pressure loss. The pressure loss has a great impact on the performance of the whole system, and may even make the liquid cooling system work abnormally. Therefore, for the aircraft liquid cooling system, the flow calibration needs to learn from the flow measurement principle of differential pressure flowmeter, and carried out the ground experiments of flow calibration. Based on the principle of the differential pressure method, design and establish the experimental platform to conduct the flow calibration of the aircraft liquid cooling system, and the corresponding flow rate curve can be obtained through the ground calibration experiments.

According to the flow calibration plan proposed above, the flow calibration experimental platform of the aircraft liquid cooling system is established in Figure 2.

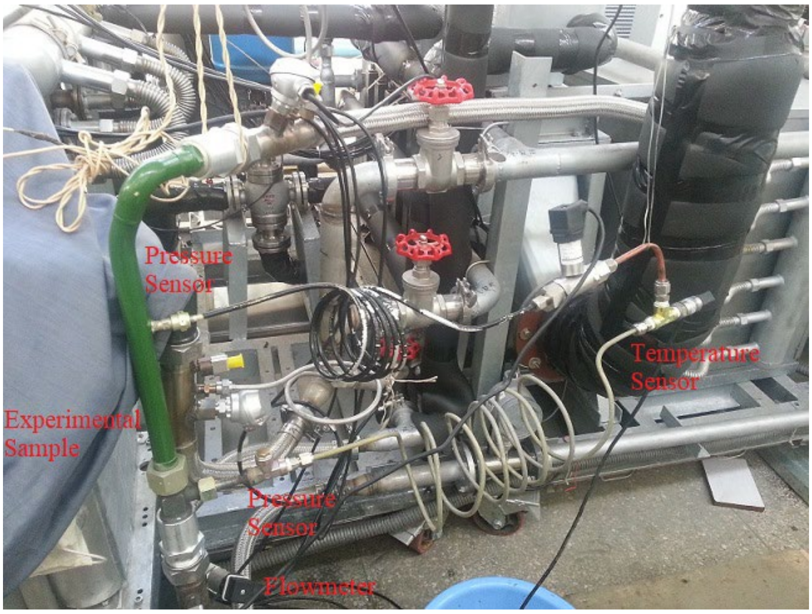

Figure 2. Schematic diagram of the aircraft liquid cooling system.

As shown in Figure 2, the cooling duct of the radar exit is a tube with variable diameters of 16 mm, 18 mm and 20 mm, and there is an elbow bend. Similar to the throttle, the pressure drop will also be caused at the inlet and outlet of the variable diameter pipe and the elbow bend. Therefore, the flow rate coefficient a can be obtained at the variable diameter pipe and the elbow bend by the ground calibration experiments, so as not to destroy the original cooling system layout or increase the additional pressure drop.

The experimental system consists of 7 parts: a pump, a filter, a heater, an imported valve, a flowmeter, an exported valve and an experimental sample. The connection of the flow calibration experimental system is shown in Figure 3.

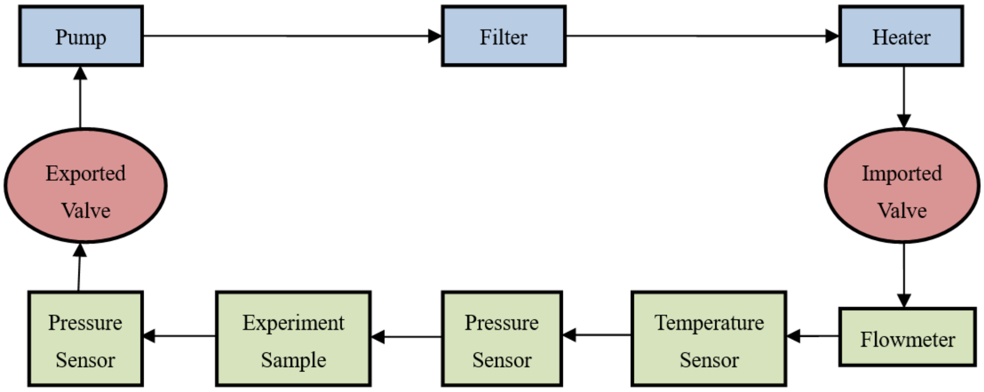

Figure 3. Diagram of connection of experimental platform.

As shown in Figure 3, the pump is used to provide continuous fluid; the heater is mainly used to regulate the temperature of the coolant and heat the coolant in the experimental system; the temperature sensor is used to measure the temperature of the coolant; the flowmeter is used to measure the flow of the coolant in the experiment sample; the function of the inlet valve is to adjust the liquid pressure into the entrance of the experiment sample by adjusting the opening degree of the inlet valve; pressure sensors are used to measure the pressure before and after the experiment sample. The pipe, which needs to be detected, is first connected to the experiment platform. Under different pressures and temperatures, the flow of the ethylene glycol through the pipe is adjusted by the pump in the experimental platform, and the pressure drop at the import and export of the experimental sample is measured by the pressure sensors, which are set before and after the experimental sample.

On the ground experimental platform of the standard flow device, the temperature, pressure and flow of the liquid cooling system are changed according to the experimental requirements, and the relation curve of the pressure drop and flow can be obtained, and the correction curve of the temperature and pressure can be obtained at the same time. The coolant is pressurized in the liquid pump, and filters into the electric heater through the filter. When the coolant is heated to the experimental required temperature, the coolant is flowing into the experimental tube through the regulating value. Then, the coolant flows back to the liquid pump through the flow control valve, and the circulation process is completed. The temperature and the flow in the pipeline remain unchanged, and the relation curve of the flow pressure drop will be obtained by changing the coolant inlet pressure of the system. The pressure drop and flow remain unchanged, and the relation curve of the flow pressure drop will be obtained by changing the coolant temperature.

4. Results and Discussion

4.1. Influence of the Temperature

When the imported valve pressure of the coolant in the pipe is 200 kPa and the coolant temperatures in the pipe are 20 °C, 40 °C and 60 °C, respectively, the relation curve of the coolant flow and the coolant pressure drop are shown in Figure 4. At the same time, we have fitted three functions between the flow and the pressure drop when the temperatures are 20 °C, 40 °C and 60 °C, and the three fitted functions are as follows:

$$\Delta P = -4.26148 + 0.16099G + 0.00106G^2 \quad \left(T = 20\,^\circ\mathrm{C}\,, P_{imported} = 200\ \mathrm{kPa}\right) \tag{7}$$

$$\Delta P = 0.67357 - 0.00217G + 0.00224G^2 \quad \left(T = 40\,^\circ\mathrm{C}\,, P_{imported} = 200\ \mathrm{kPa}\right) \tag{8}$$

$$\Delta P = 4.70683 - 0.14571G + 0.00329G^2 \quad \left(T = 60\,^\circ\mathrm{C}\,, P_{imported} = 200\ \mathrm{kPa}\right) \tag{9}$$

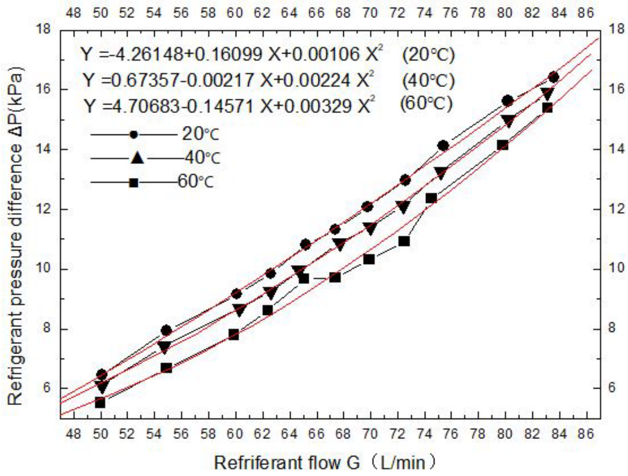

Figure 4. Variation in pressure drop with flow rate (imported pressure 200 kPa).

As shown in Figure 4, when the pressure of the coolant in the pipe is 200 kPa, the influence of the pressure drop on the flow measurement is relatively constant as the flow increases; under different coolant flow conditions, the increasing amplitude of the coolant pressure drop with the flow increasing almost remains the same. At the same time, the influence of the temperature on the flow measurement also cannot be ignored, and the influence of the temperature on the measured value of pressure drop is about 9% under the same coolant flow condition.

When the imported valve pressure of the coolant in the pipe is 350kPa and the coolant temperatures in the pipe are 20 °C, 40 °C and 60 °C, respectively, the relation curve of the coolant flow and the pressure drop is shown in Figure 5. At the same time, we have fitted three functions between the flow and the pressure drop when the temperature is 20 °C, 40 °C and 60 °C, and the three fitted functions are as follows:

$$\Delta P = 0.27686 + 0.00813G + 0.00225G^2 \quad \left(T = 20\ ^\circ\mathrm{C}\,, P_{imported} = 350\ \mathrm{kPa}\right) \tag{10}$$

$$\Delta P = -2.79757 + 0.10229G + 0.00140G^2 \quad \left(T = 40\ ^\circ\mathrm{C}\,, P_{imported} = 350\ \mathrm{kPa}\right) \tag{11}$$

$$\Delta P = 1.46309 - 0.04899G + 0.00264G^2 \quad \left(T = 60\ ^\circ\mathrm{C}\,, P_{imported} = 350\ \mathrm{kPa}\right) \tag{12}$$

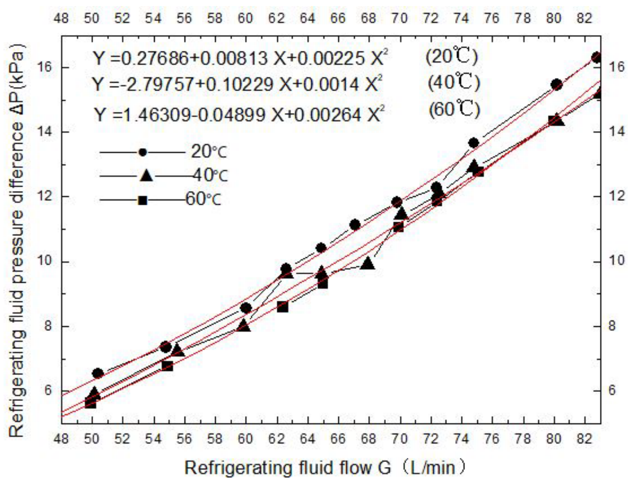

Figure 5. Variation of pressure drop with flow rate (imported pressure 350 kPa).

As shown in Figure 5, the coolant temperature will affect the accuracy of the flow measurement. When the imported pressure of the coolant is 350 kPa, compared with the imported pressure 200 kPa in Figure 3, the influence of the temperature on the flow measurement under two imported pressures above are very close. For the pressure drop measurement, the influence of the coolant temperature is smaller, and the maximum error is less than 7%.

4.2. Influence of the Pressure

When the coolant temperature in the pipe is 20 °C, 40 °C and 60 °C, the imported pressure of the coolant is set to 200 kPa and 350 kPa, and pressure drops under different flow are measured, respectively. As the flow increases, variation curves of the pressure drop are shown in Figures 6–8, respectively.

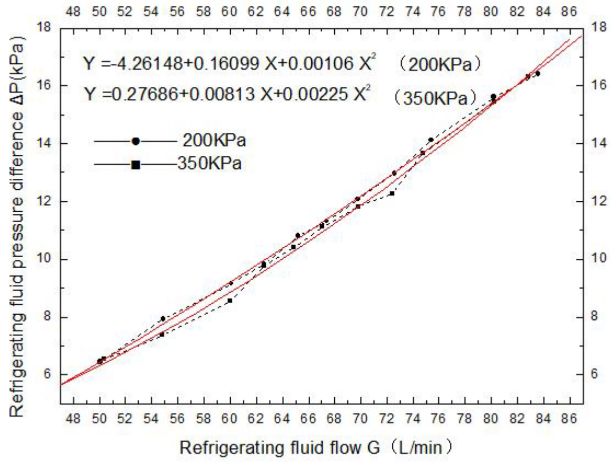

Figure 6. Variation of pressure drop with flow rate (temperature 20 °C).

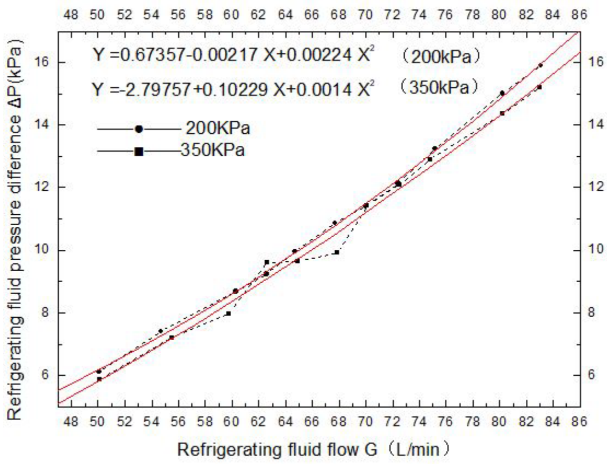

Figure 7. Variation of pressure drop with flow rate (temperature 40 °C).

As shown in Figures 6–8, the influence of the pressure on the flow measurement of the coolant is relatively smaller, and when the temperature increases, the influence of the pressure on the coolant flow gradually increases. From the above analysis, it can be concluded that the influence of the temperature on the coolant flow measurement is relatively larger. This influence has little relation with the flow changing, and gradually decreases as the pressure increases; the influence of the coolant pressure on the coolant flow measurement gradually increases as the coolant temperature increases.

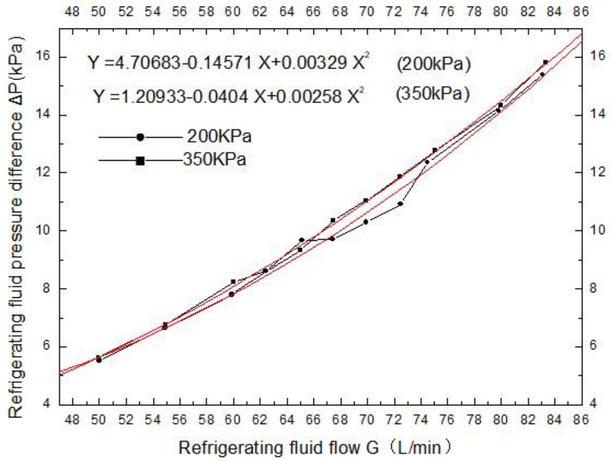

Figure 8. Variation of pressure drop with flow rate (temperature 60 °C).

5. Conclusions

According to the flow characteristics of the fluid in the variable diameter pipe and the elbow bend, a new experimental method of measuring the flow coefficient is proposed in this paper through the differential pressure flow counter, which is developed by the differential pressure flow rate measurement principle.

The volume of the experimental equipment used in the flow calibration experiments proposed in this paper is very small, which can reduce the experimental modification work. It is not necessary to install the throttle device in the pipe of the liquid cooling system, which reduces the risk of the aircraft liquid cooling system leakage. This method does not destroy the original cooling system layout or increase the additional pressure loss. The flow coefficient calibration method proposed in this paper can also be applied to the flight text of other types of aircraft liquid cooling system.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

$p_1{}'$	average pressure of the fluid at Section 1;
$p_2{}'$	average pressure of the fluid at Section 2;
ρ_1	density of the fluid at Section 1;
ρ_2	density of the fluid at Section 2;
μ	contraction coefficient of the stream;
G	flow rate of coolant in the pipe.
u_1	flow velocities at Section 1;
$u_2{}'$	flow velocity at Section 2;
A_1	area of Section 1;
A_2	area of Section 2;
β	diameter ratio of the throttle device;

References

1. Zheng, X.; Yang, W. Heat transfer coefficient of film cooling with ellipse-shaped tab. *Trans. Nanjing Univ. Aeronaut. Astronaut.* **2016**, *33*, 155–165.
2. Li, J.; Jiang, Y.; Wang, Y.; Meng, E.; Li, C. Numerical calculation and experimental investigation on airborne three-stream plate-fin condenser. *J. Nanjing Univ. Aeronaut. Astronaut.* **2017**, *49*, 382–388. (In Chinese)
3. Zhang, J. A new way of the flow meter of pressure difference. *Autom. Petro-Chem. Ind.* **2004**, *5*, 87–89. (In Chinese)
4. Li, Y.; Wu, Z. Theoretical analysis and experimental investigation on DIS change measurement by angle pipe. *Irrig. Drain.* **1995**, *14*, 6–11. (In Chinese)
5. Sun, Z.; Zhou, J.; Zhang, H. Numerical simulation and experimental research on measurement characteristics of elbow meter. *Chin. J. Sens. Actuators* **2007**, *20*, 1413–1415. (In Chinese)
6. Li, Y.; Liao, W.; Tian, J. Regression analysis concerning discharge and pressure difference of elbow and calculation of discharge coefficient. *J. Xi'an Univ. Technol.* **1998**, *14*, 373–376. (In Chinese)
7. Silva, F.S.; Velazquez, M.T.; Hernandez, J.R. Experimental study for the use of elbows as flowmeters. *Comput. Stand. Interfaces* **1999**, *21*, 185. [CrossRef]
8. Zheng, J.; Liang, G.; Cheng, Y. Experimental study on the characteristic of elbow flowmeter. *J. China Inst. Metrol.* **1999**, *2*, 41–46. (In Chinese)
9. Tian, Y.; Wang, Y.; Guo, S.; Liu, F.; Hu, Z. Application of common flowmeters. *Contemp. Chem. Ind.* **2011**, *40*, 1294–1296. (In Chinese)
10. Ahrens, M.; Nestler, B.; Klein, S.; Lucas, P.; Petter, H.T.; Damiani, C. An experimental setup for traceable measurement and calibration of liquid flow rates down to 5 nL/min. *Biomed. Tech. Biomed. Eng.* **2015**, *60*, 337. [CrossRef] [PubMed]
11. Doihara, R.; Shimada, T.; Cheong, K.H.; Terao, Y. Liquid low-flow calibration rig using syringe pump and weighing tank system. *Flow Meas. Instrum.* **2016**, *50*, 90–101. [CrossRef]
12. Longbo, M.A.; Zheng, J.; Zhao, J. Research on the flow measurement error model of the diverter in the liquid flow calibration facilities. *Chin. J. Sens. Actuators* **2015**, *28*, 515–520.
13. Nakada, T.; Zheng, Y.; Sakurai, Y. A liquid flow rate measurement method using an AE sensor: Measurement of steady flow rate. *Trans. Jpn. Hydraul. Pneum. Soc.* **2013**, *44*, 49–54. [CrossRef]
14. Wang, Q. The application and the development of flowmeters. *Sci. Technol. Inf.* **2008**, *3*, 32. (In Chinese)
15. Guo, X.; You, X.; Li, L.; Du, W. A new orifice flowmeter with different diameter. *J. Henan Vocat. Tech. Teach. Coll.* **1994**, *22*, 13–15. (In Chinese)
16. Wu, C. *Hydraulics*; Higher Education Press: Beijing, China, 1982. (In Chinese)
17. Feng, W. Coolant flow measurement of aircraft liquid cooling system based on differential pressure method. *ACTA Metrol. Sin.* **2014**, *35*, 248–251. (In Chinese)
18. Cui, Y.; Shi, H.; Chen, C. Flow measurement and calculation of aircraft liquid cooling system. *Value Eng.* **2017**, *36*, 93–96. (In Chinese)
19. Yulang, C.T. *The Flow Measurement Manual*; Chinese Metrology Press: Beijing, China, 1982. (In Chinese)
20. Liang, G.; Cai, W. *The Flow Measurement Technology and Instruments*; China Machine Press: Beijing, China, 2002. (In Chinese)
21. Su, Y. *Flow Measurement and Test*; China Metrology Press: Beijing, China, 1992. (In Chinese)