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VERIFICATION TEST OF A THREE-SURFACE-MULTI-LAYERED CHANNEL TO REDUCE MHD PRESSURE DROP

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ABSTRACT

A three-surface-multi-layered channel is one of the possible methods for reducing the magnetohydrodynamic (MHD) pressure drop in the liquid metal blanket of a fusion reactor. An MHD flow experiment was conducted to verify the MHD pressure drop reduction by using the three-surface-multi-layered channel with ceramic insulator in this study. We used a PbLi flow loop and a magnet generating a magnetic field of up to 1.8 T. The experimental results were compared with numerical predictions. The pressure drop obtained by the experiment was one-tenth of the numerical one for a conducting channel. Though the measured pressure drop shifted slightly, the result was reasonable since it showed good agreement with numerical predictions as the result of modifying the shift. In this study, it was verified that the three-surface-multi-layered channel works as it had been supposed and the MHD pressure drop was reduced by using this channel.

1. INTRODUCTION

MHD pressure drop reduction is one of the most important R&D issues in liquid metal fusion blankets. A three-surface-multi-layered channel shown in Fig. 1, which consists of a thin metal layer and a ceramic insulating layer on three of the four channel wall's inner surfaces, is an advanced concept to reduce the MHD pressure drop (Hashizume, 2006). In order to validate this concept, a liquid metal flow experiment has been conducted by means of an open annular channel where one surface of the channel had the multi-layered structure with a thin metal layer and Teflon insulating one (Aoyagi *et al*., 2010). Since the channel was axial symmetrical, the flow should have been two dimensional. The experimental result showed that the MHD pressure drop was reduced more by using thinner metal layer as was predicted in the 2D MHD numerical analysis. This result means that the MHD pressure drop is reduced by an ideal three-surface-multi-layered channel which is completely insulated between the metal layer and structural wall. However at the actual fusion blanket channel, the insulator must be ceramic which is much more fragile than Teflon and besides 3D MHD effect such as the current flowing in the streamwise direction could affect the pressure drop. In this study, therefore, we verify the MHD pressure drop reduction experimentally by means of a closed straight channel with three-surface-multi-layered structure and ceramic insulating.

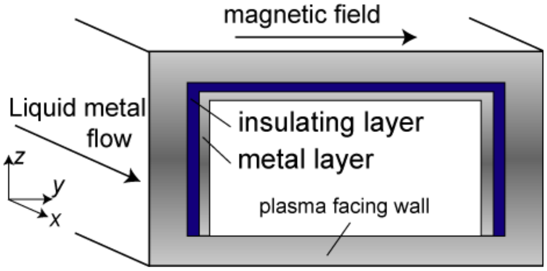

Fig. 1 Schematic view of the Three-surface-multi-layered channel

2. EXPERIMENTAL METHOD

2.1 Experimental Apparatus

This MHD flow experiment is conducted using an MHD experimental loop at UCLA (Smolentsev *et al*. 2012; Li *et al*. 2012). Layout of the loop is sketched at the Fig. 2. The loop system consists of a melting tank, an electromagnetic (EM) pump, an EM flow meter, a test channel and circular pipes with outer diameter of 25.4 mm to connect the foregoing components. A sub loop sketched at Fig. 3 is connected to the test channel in order to measure the pressure differences. Thermocouples are installed in the melting tank and attached on the pipe and buffer tanks as shown in Figs. 2 and 3. The working fluid is the PbLi eutectic alloy. A uniform magnetic field up to 1.8 T is applied transversely against the flow for 1 m in the streamwise direction. The test channel's structural wall is made of 316 grade of austenite stainless steel (SUS 316). As a ceramic insulating layer, silica is painted on the inner surface of the structural wall. The coating thickness is 0.05 – 0.15 mm. The metal layer of a 0.1 mm thick SUS 316 is installed in the channel. The dimensions of the test channel are 0.8 m in the streamwise direction, 20 mm in the inner width and 8 mm in the inner height. The wall thicknesses are 3 mm in the non-layered wall and 5 mm in the three layered walls, respectively. These channel dimensions were optimized for a blanket cooling channel (Aoyagi *et al*., 2011). The space between the metal layer and the structural wall are closed by welding at the both ends of the channel in order to prevent the fluid invading into the space. Corn-shaped connectors are mounted at the both ends of the test channel to connect the circular pipe of the experimental loop and the rectangular test channel. These connectors are not insulated.

The experimental parameters are the magnetic field intensity (0~1.8 T), the flow velocity (0.1~2.0 m/s) and the operating temperature (270 ~ 350 °C). Maximum flow velocity is limited by the EM pump capacity and is 1.5 m/s for 1 T, 1.0 m/s for 1.5 T and 0.5 m/s for 1.8 T, respectively. Non-dimensional parameters are, in the cases of 270, 300 and 350 °C, $Ha < 3.2\times10^2$, 3.5×10^2 and 3.8×10^2 and $Re < 7.8\times10^4$, 8.8×10^4 and 1.1×10^5, respectively, where Ha and Re are a Hartmann number and a Reynolds number respectively and they are defined by Eqs.(1) and (2):

$$Ha = BL\left(\frac{\sigma}{\mu}\right)^{0.5}, \qquad (1)$$

$$Re = \frac{\rho u L}{\mu}\ . \qquad (2)$$

The nomenclatures are described at the end of paper. Half width of the channel of 0.01 mm is used as characteristic length L in the foregoing Ha and Re. Reynolds number based on the hydraulic equivalent diameter is $Re < 2.0\times10^5$ for 300 °C.

2.2 Measurement Principle

2.2.1 Flow rate

Flow rate is measured by the EM flow meter installed downstream of the pump. The EM flow meter consists of electrodes at the top and bottom of the pipe and a pair of permanent magnets existing at the both side of the pipe. The flow rate can be calculated from the voltage between the electrodes and the magnetic field.

2.2.2 Pressure difference

Since it is difficult to measure directly the pressure of the high temperature PbLi, we used an indirect measurement system (Li *et al*., 2012) as shown in Fig. 3. Four buffer tanks are connected to the test channel and contain the liquid PbLi and Ar gas with fluid surface in the tanks. Then the pressure difference of the gas Ar is measured by a differential pressure sensor. Four valves connecting the tanks and the sub loop enable us to measure three different sections; upstream region (A-B), downstream region (C-D) and entire the test section (A-D). Since the pressure difference measured in this experiment is up to 14 kPa and is relatively small compared with the absolute pressure of about 100 kPa, the measured pressure drop is susceptible to error caused by even slight initial pressure difference due to small temperature change or something. Then the experimental results are modified to make the pressure drop zero at the zero velocity. It is assumed that the amounts of the shift are the same among the data obtained in the same magnetic field and temperature and do not depend on the velocity.

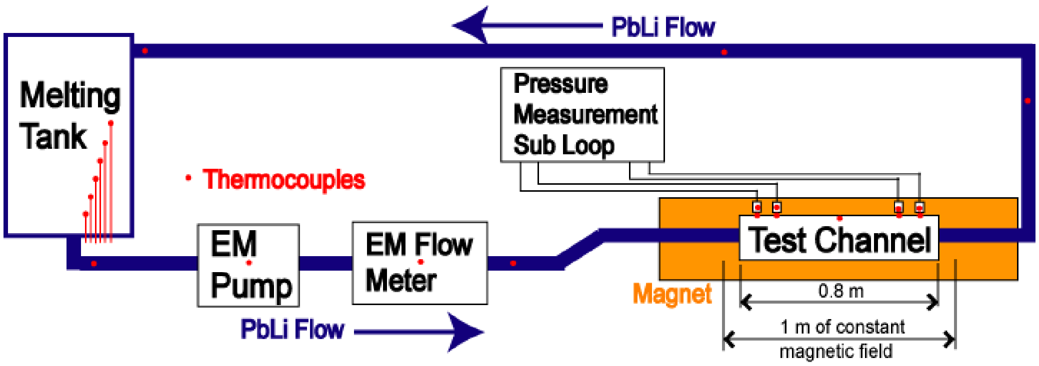

Fig. 2 Schematic view of the PbLi loop system

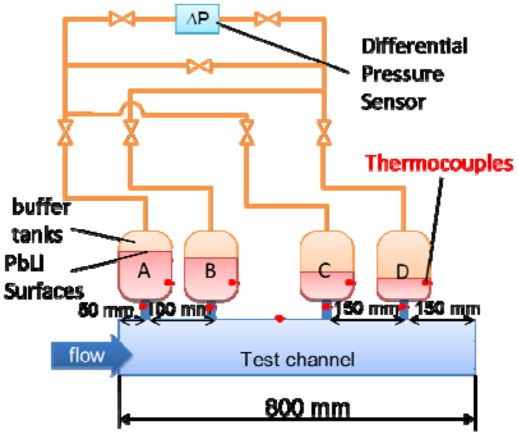

Fig. 3 Schematic view of the sub loop for differential pressure measurement

3. NUMERICAL PREDICTION

In order to analyze whether the three-surface-multi-layered channel works as it has been supposed or not in the experiment, numerical simulation is conducted with 2D-fully-developed MHD laminar flow assumption. The governing equations are a two-dimensional steady Navier-Stokes equation and a Poisson equation in terms of the electrostatic potential given by Eq. (3) and (4) respectively:

$$\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)+\sigma\left(\frac{\partial \phi}{\partial z}-uB\right)B=0\ , \tag{3}$$

$$\frac{\partial}{\partial y}\left(\sigma\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\sigma\frac{\partial \phi}{\partial z}\right)-\frac{\partial}{\partial z}\left(\sigma uB\right)=0\ . \tag{4}$$

The x-, y- and z-directions are described in Fig. 1. These equations are discretized by a finite volume method and solved iteratively.

Two different models are calculated. One is the three-surface-multi-layered channel as shown in Fig. 1, and the other is simple conducting wall without insulator. If the insulating coating is perfect and there is no 3D effect in the experiment, the experimental result should correspond to the calculation for the three-surface-multi-layered channel. On the other hand, if the coating has defections and the thin metallic layer has a lot of electrical contact with the structural wall, the experimental result could be close to the conducting wall one.

The calculation is conducted for the same parameters of the velocity, magnetic field and temperature as those tested in the experiment. Table 1 shows the physical properties of the PbLi and SUS 316 used in the calculation.

4. RESULTS AND DISCUSSIONS

4.1. Pressure drop for low magnetic field

Figures 4 and 5 show the pressure drop in the downstream region (C-D) obtained by the experiment and the calculations in the case of 300 °C and 0.5 and 1.0 T, respectively. Although the experimental data is much smaller than the calculation ones for the conducting channel without insulating coating indicated by thick lines, there are comparatively large differences between the experimental results and the numerical ones for the three-surface-multi-layered channel indicated by thin lines in the case of high velocity. Turbulence is considered to increase the pressure drop in the experiment. It is well known that the MHD flow transit from the laminar flow to the turbulent one in the case of Ha/Re < 1/200 (Krasnov *et al.*, 2004). The value of Ha/Re becomes smaller than 1/200 in the cases of u > 0.44 m/s at B=0.5 T or u > 0.88 m/s at B=1.0 T. Therefore, in such cases of low Ha/Re, large pressure drop is obtained in the experiment.

Table 1 Physical properties

	PbLi Conductivity (S/m)	PbLi viscosity (Pa·s)	SUS316 conductivity (S/m)
270 °C	7.97×10^{5}	2.46×10^{-3}	1.08×10^{6}
300 °C	7.89×10^{5}	2.15×10^{-3}	1.05×10^{6}
350 °C	7.76×10^{5}	1.77×10^{-3}	1.00×10^{6}

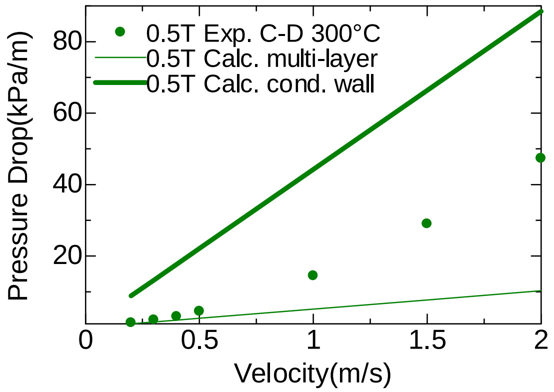

Fig. 4 Pressure drop in the region C-D at 0.5 T, 300 °C

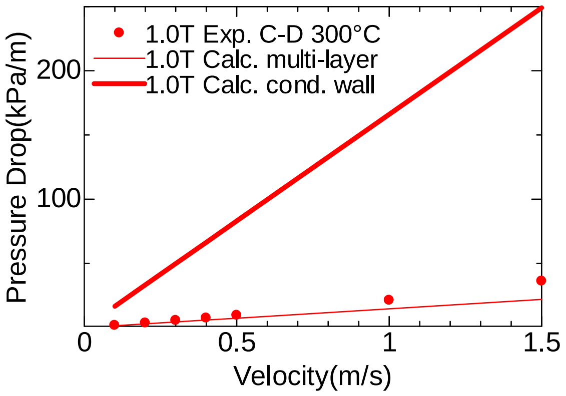

Fig. 5 Pressure drop in the region C-D at 1.0 T, 300 °C

4.2 Pressure drop for high magnetic field

Figure 6 shows the pressure drop in the downstream region (C-D) obtained by the experiment and the calculations in the case of 300 °C and 1.8 T. In the case of 1.8 T, the experimental result is almost corresponding to the calculation for the three-surface-multi-layered channel indicated by a thin line and is one-tenth the value of the calculation for the conducting channel without insulating coating indicated by a thick line. This result represents the MHD pressure drop is reduced drastically by the three-surface-multi-layered channel.

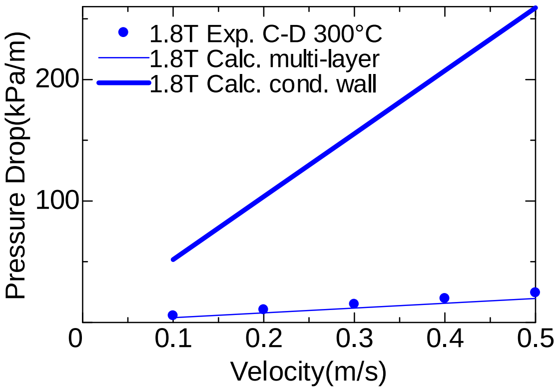

Fig. 6 Pressure drop in the region C-D at 1.8 T, 300 °C

4.3 Velocity dependency

Figures 7 and 8 show the change in the pressure drop against the mean flow velocity in the upstream (A-B) and downstream (C-D) regions, respectively. Dashed lines are linear approximation expressions for the experimental data by the least squares method. The solid lines are the numerical data for the three-surface-multi-layered channel. Negative pressure drop is measured in the case of 1 T and 0.1 m/s. The extrapolated values are not zero at the zero velocity for almost all cases. This can be inferred that the initial pressure difference between the buffer tanks due to different level of the liquid PbLi in the tank.

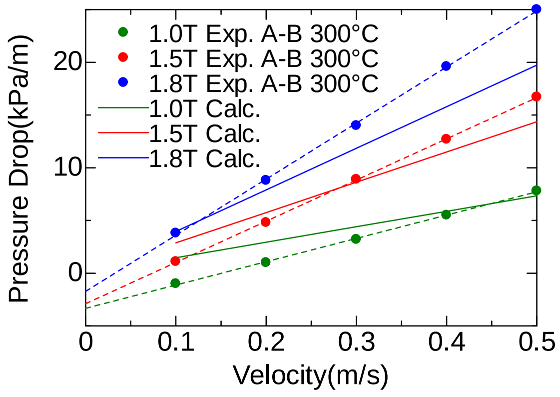

Fig. 7 Pressure drop change against the velocity in the region A-B at 300 °C

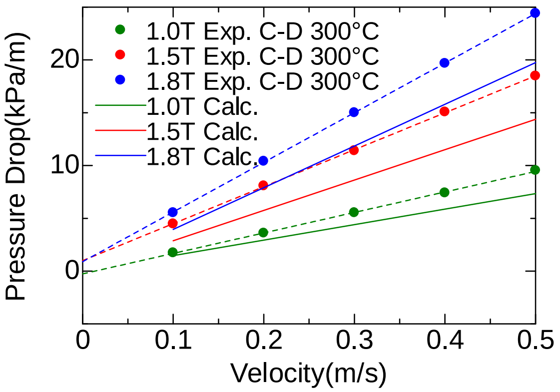

Fig. 8 Pressure drop change against the velocity in the region C-D at 300 °C

Figures 9 and 10 show the modified pressure drop with respect to the mean flow velocity. The pressure drop changes almost linearly against the velocity in all of the cases as is predicted by the numerical result. The experimental results are close to the numerical ones but there exists some gap between them. The differences are about 30 % in the region A-B and about 20 % in the region C-D, respectively.

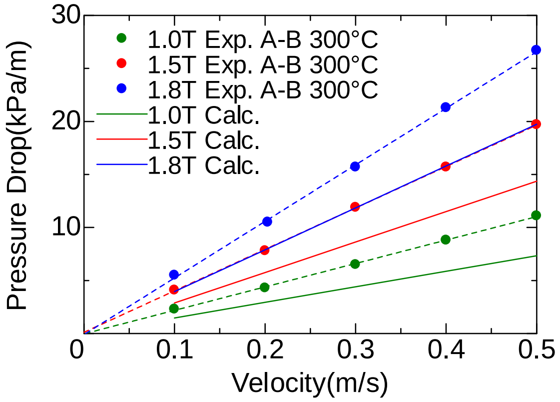

Fig. 9 Modified pressure drop change against the velocity in the region A-B at 300 °C

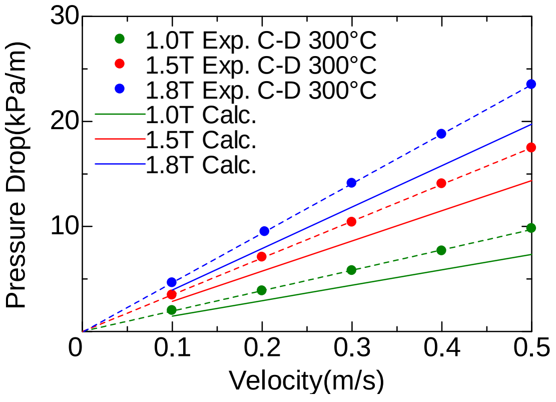

Fig. 10 Modified pressure drop change against the velocity in the region C-D at 300 °C

4.4 Temperature dependency

As shown in Table 1, there are temperature dependencies in the physical properties especially in viscosity. In order to examine whether the pressure drop shows characteristic changes depending on the physical properties change, we have tested for three different temperatures. Figures 11 and 12 show the pressure drop change depending on the temperature. The pressure drop changes slightly depending on the temperature. Since the viscosity and the electric conductivities decrease with the temperature, both the Lorenz force and the friction force decrease and hence the pressure drop is reduced. The differences depending on the temperature are well corresponding to those obtained by the numerical simulation.

4.5 Magnetic field dependency

Figures 13 and 14 show the changes in the pressure drop against the magnetic field in the upstream (A-B) and downstream (C-D) regions, respectively. Dashed lines are quadric approximation expressions for the experimental data by the least squares method. The pressure drop shows the quadric change against the magnetic field as given by the basic MHD theory in all the temperature conditions.

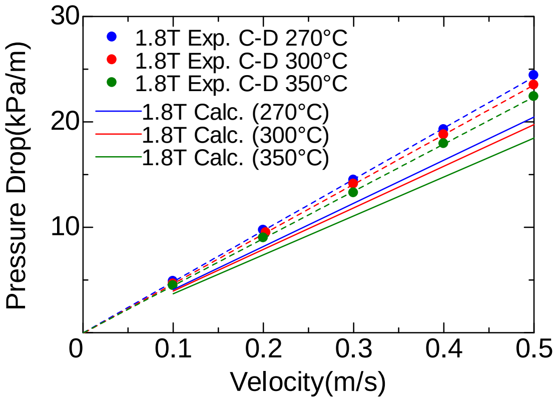

Fig. 11 Modified pressure drop change depending on the temperature in the region A-B at 1.8 T

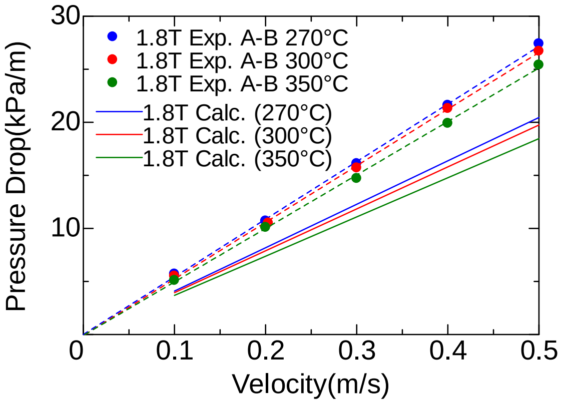

Fig. 12 Modified pressure drop change depending on the temperature in the region C-D at 1.8 T

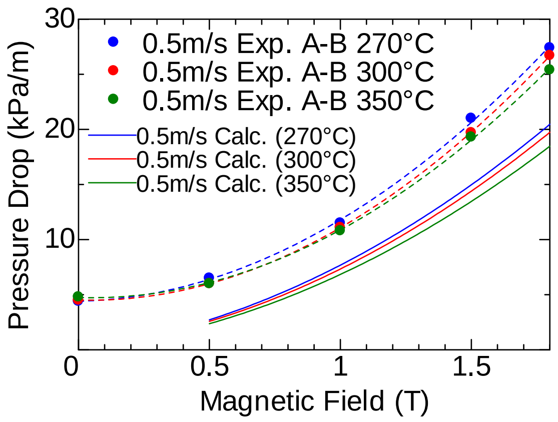

Fig. 13 Modified pressure drop change against the magnetic field in the region A-B at 0.5 m/s

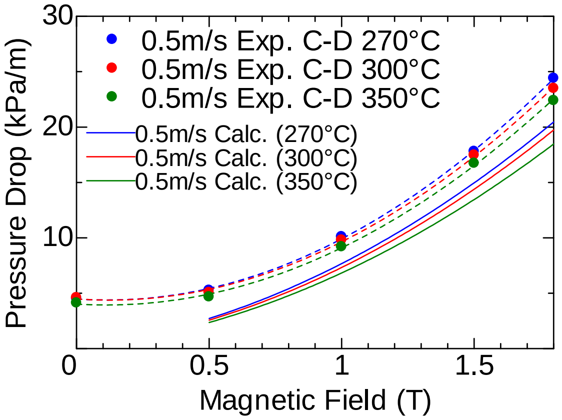

Fig. 14 Modified pressure drop change against the magnetic field in the region C-D at 0.5 m/s

Figures 15 and 16 show the differences between the modified experimental data and the numerical ones. Solid and dash lines are the net Lorentz force and friction force per unit volume acting on the fluid, respectively, obtained numerically. In the case of the magnetic field larger than 1 T, the differences change almost linearly against the magnetic field. This means that the difference between the experimental results and calculated ones is possibly caused by the friction force which changes linearly against the magnetic field. If the Lorentz force affected the difference, the difference should have changed nonlinearly like the change in the Lorentz force described in Fig. 15 and 16. Therefore there is no more Lorentz force in the experiment than those in the calculation. It means that the insulating coating works well.

5. CONCLUSIONS

We conducted the MHD flow experiment with the three-surface-multi-layered channel and the PbLi as working fluid. The results are summarized as follows:

(1) It was verified that the MHD pressure drop was reduced by using the three-surface-multi-layered channel under the high magnetic field of up to 1.8 T.

(2) As the result of modifying zero shifts, the experimental results showed qualitatively good agreement with the numerical results against changes in the velocity, the temperature and the magnetic field.

(3) The experimental results were slightly larger than those by the numerical simulation. The amounts of the increase were about 30 % in the upstream region and about 20 % in the downstream region, respectively.

(4) Since the differences between the modified experimental data and the numerical ones changed linearly against the magnetic field, no more Lorentz force acted in the experiment as compared to that in the calculation. Therefore the insulating coating works well as it had been supposed.

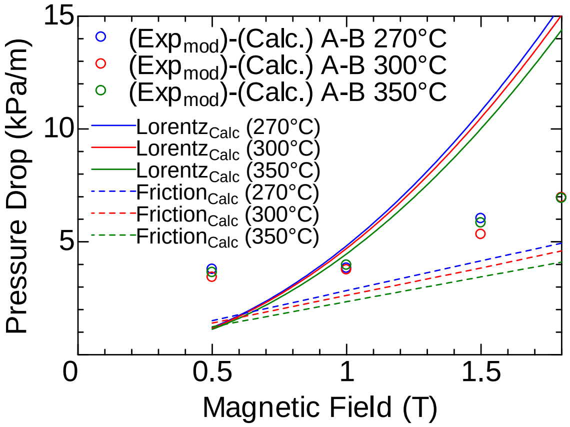

Fig. 15 Difference between the modified experimental data and the numerical ones in the region A-B at 0.5 m/s

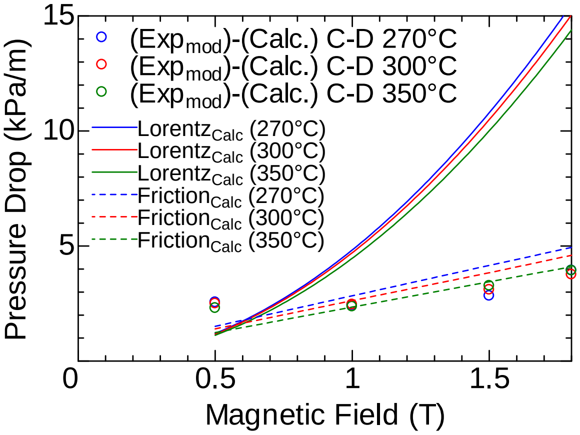

Fig. 16 Difference between the modified experimental data and the numerical ones in the region C-D at 0.5 m/s

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NOMENCLATURE

B	Magnetic field	[T]
L	Characteristic length	[m]
u	Flow velocity in the streamwise direction	[m/s]

Greek Letters

ϕ	Electric potential	[V]
μ	Viscosity	[Pa·s]
ρ	Density	[kg/m^3]
σ	Electric conductivity	[S/m]

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