Experimental investigation of forced convective heat transfer in cylindrical pipe flow

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***Abstract*—Forced convective heat transfer in cylindrical pipe flow plays an important role in many technical cooling system. Heat transfer coefficients are vary with flow regime. Much remains to be study for providing experimental data for transitional regime. Reliable prediction of heat transfer coefficients for transitional flow is still challenging tasks. In this study, I focused on forced convective heat transfer in cylindrical pipe flow for transitional regime in particular high Prandtl number. Moreover, the measurement of wall friction coefficients were also performed in this study. The engineeres is frequently interested in pressure drop which is related to determine pump or fan power equipments.**

***Index Terms*—Forced convection, Nusselt number, Wall friction, transitional, Cylindrical pipe flow**

I. Introduction

Forced convective heat transfer in cylindrical pipe flow plays an important role in many technical cooling systems. These coolant technology is used wide varaety of coolant applications such as electric devices, automotive, and plant factory. Considering heat transfer issues, heat transfer coefficients are one of the most important numbers.

Much remains to be studied for providing experimental data for high Pramdlt number and laminar-to-turbulent transitional regime. In this study, I focus on forced convective heat transfer in cylindrical pipe flow in particular high Pramdlt number and transitional regime. Shell Heat Transfer Oil was used as a operating liquid.

II. Emperical correlations

A. Friction coefficients

Skin friction coefficient for laminar flow is descrived following equation.

$$C_{f,lam} = \frac{16}{Re_b} \tag{1}$$

Konakov [2] showed skin friction coefficient for turbulent flow.

$$C_{f,turb} = 0.25(1.8log(Re_b) - 1.5)^{-2} \tag{2}$$

Note that these skin friction coefficient just suitable for no-heating condition, constant fluid properties. In this thesis, we provide heat to the pipe. Therefore, the fluid properties change depend on the temperature.

B. Heat transfer coefficients

Gunielinski [3] showed correlations for each flow regime, laminar and turbulent, respectively. Morover, he presented transitional flow regime as a liner interpolation between laminar and turbulent flow. From general dimensional analysis, Nusselt number represents function of Reynolds number (Re) times Prandtl number (Pr) as following equation.

$$Nu = \alpha \cdot Re^{\pi_\beta} \cdot Pr^{\pi_\gamma} \tag{3}$$

Here, factors α, β and γ are constant value depend on flow regime and calcurated from numerical experimental results. Gunienski [3] showed correlations for each flow regime laminar and turbulent, respectively. Gunienski [3] showed calculation method for laminar flow.

$$Nu_{lam} = (3.66^3 + 0.7^3 + (1.615(Re_b Pr_b \frac{d_i}{L})^{1/3})^3)^{1/3} \tag{4}$$

Gunienski [3] showed calculation method for turbulent flow.

$$Nu_{turb} = \frac{\frac{C_f}{2Re \cdot Pr_b}}{1 + 12.7\sqrt{\frac{C_f}{2}}(Pr_b^{2/3} - 1)} \cdot (\frac{Pr_b}{Pr_w})^{0.11} \tag{5}$$

The range is

$$0.1 << Pr_b << 1000, 10^4 << Re_b << 10^6. \tag{6}$$

He presented transitional flow as a liner interpolation between turbulent and laminar flow. (See "science problems and interesting issue" section No.12.)

$$Nu_m = (1 - r)Nu_{m,lam} + rNu_{m,turb} \tag{7}$$

$$r = \frac{Re_b - 2300}{10^4 - 2300} \tag{8}$$

III. Experimental setup

Figure. 1 shows experimental loop. The experimental loop consists of heat exchanger, pump, coriolis mass flow rate, welder, reservoir, and test section basically. Heat exchenger keep thermal stationary condition in flow pipe. Mass flow rate is controlled by pump and baypass valve C which is located in a parallel. The pipe is thermal isolated, surrounded with glass wool.

Figure. 2 shows velocity and thermal boundary layer development vary with horizontal axis in a test section. Velocity and thermal profile are shown blue and red color, respectively. The

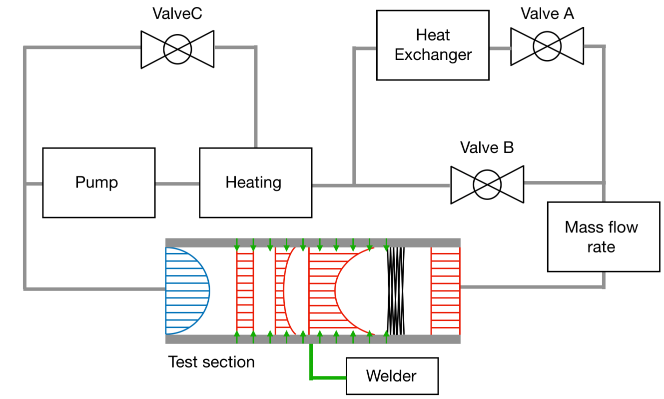

Fig. 1. Process flow diagram of the test facilities including test section.

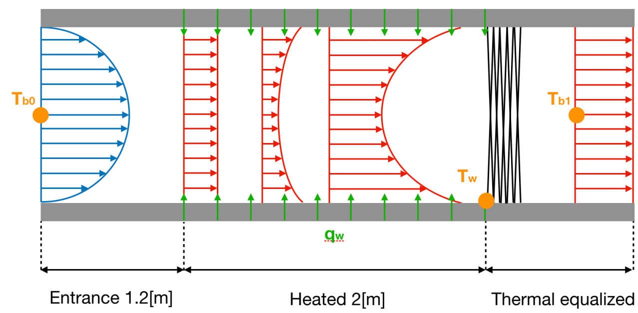

Fig. 2. Velocity (blue) and thermal (red) boundary layer development vary with horizontal axis in a test section.

test section is made of stainless steel (1.4301) with an inner diameter di=12mm and outer diameter do= 15mm. Highly accurate resistance thermall probes (PT-100) are used to find out the inlet and outlet bulk temperature (Tib , Tob) and wall temperature Tw. Moreover, thermocouple 'Type-K' are used to take temperature gradient in flow direction.

The test section consist of entrance, heated and thermal equalized part.

1) Entrance part
   The first part of test section is 1.2 [m] length entrance part which is sufficiently long to ensure dynamically developed flow condition at the exist. The bulk temperature (Tb0) at this section were measured by PT-100.
2) Heated part
   The second part of test section is 2 [m] length heated part which is sufficiently long to ensure thermaly fully developed flow condition at the exist. The tube wall were heated electrically by welder which provide high current and low voltage to keep the uniform heat flux condition in a inner pipe flow. Convective heat transfer is independent with horizontal axis in fully developed flow, constant heat flux condition. The wall temperature (Tw) at the exist of this section were measured by PT-100.
3) Thermal equalized part
   The third part of test section is thermall equalized part which is including static mixture. Static mixture forms turbulent and vortex. Then, the thermal profile of heated exist mix together. At the end, the bulk temperature(Tb1) are measured.

A. *Length-to-diameter ratio*

The length-to-diameter ratio is an important parameter to achieve the fully developed turbulent condition in the test section. Test section has an inner diameter of $D = 12mm$, and the length of $L = 2m$ which length-to-diameter ratio is $L/D = 167$. Patel et.al. [1] showed suitable the length-to-diameter ratio for fully developed turbulent flows. According to their study, they found that the minimum developing length of $L/D = 70D$. Therefore, the length-to-diameter ratio of the test section in this experimental is long enough to ensure a fully developed turbulent flow state.

B. *Conduction equation*

TPT100 sensors are attached

C. *Wall roughness*

To clarify the wall surface as a smooth pipe, wall roughness was considered. Moody diagram defined the basis of friction chart, and that can be used in practice. Nikuradse made a throughout studies of turbulent flows in pipes with a rough surface. Reynold number can be interpreted as the ratio between the rough height h and thickness of the viscous sublayer ν/u_*, as the following equation.

$$Re = \frac{hu_*}{\nu} \tag{9}$$

Here, u_* represents wall friction velocity and descrived following equation.

$$u_* = \sqrt{\frac{\tau_{wall}}{\rho_0}} \tag{10}$$

Wall roughness of a characteristic height is descrived following equation.

$$h = 4k_{rms} \tag{11}$$

In this experiment, the surface roughness of interior surfaces in stainless steel (1.4301) is approximately $k_{rms} = 5\mu m$. TableI shows roughness consideration in this experiment. It is shown that the Reynolds number in this experiment is less than 1. Thus, the interior wall surface in the experimental setup is considered to be a smooth surface.

TABLE I
ODERS OF EACH TERMS IN EQUATION

surface roughness	roughness height	viscous sublayer	Re
$5\mu m$	$20\mu m$	$0.4\mu m$	0.48

D. Velocity profiles

Turbulent velocity profiles for the smooth wall as following equation.

$$\overline{u} = u_* \left[\frac{1}{k} ln \left(\frac{y}{h} \right) + B' \right] \tag{12}$$

B' is a function of the Reynolds number and calcurated as following equation.

$$B' = 2.5 ln \left(\frac{h u_*}{\nu} \right) + 5 \tag{13}$$

Figure3 shows mean velocity profile....

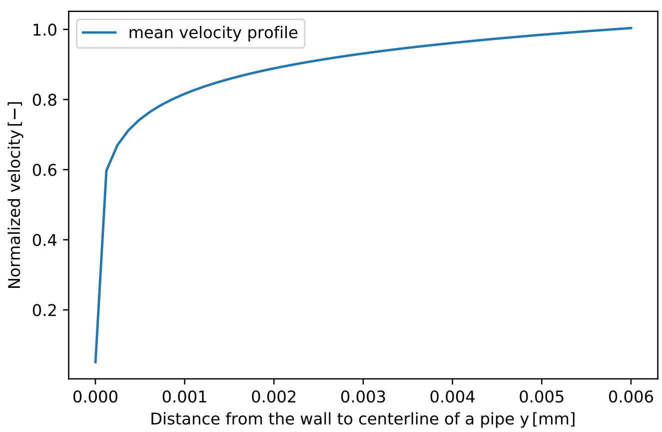

Fig. 3. mean velocity profile when Re=2300 and Pr=50.

IV. EFFECTIVE DATA PROCEDURE

V. CALUCURATION FLOW

Material properties are all temperature-dependent function. At first, material properties varies with temperature were taken. Next, I move to experimental facilities and measured temperature differences, pressure differences and mass flow rates. Finaly, Nusselt, Prandtl, Reynolds numbers and friction coefficients were calcurated by post-proccesing, LabView and MATLAB.

VI. RESULTS AND DISCUSSIONS

The aim of this research is to investigate heat transfer and friction coefficients using Water glycole $50\%/50\%$ mixture as an oparatiog liquid. In order to investigate Prandtl number throughly, first the experimental results for Pr=50 is compared with data obtained in previous studies [5] using Shell Heat Transfer Oil for Prandtl numbers Pr=50. Therefore, the validity of evaluation process for the experiment are checked.

Fig. 4. Post processing

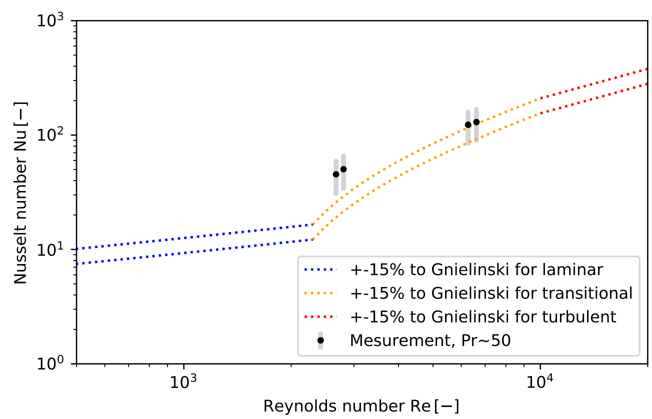

Fig. 5. Dimensionless heat transfer coefficients compared to literature data and previous studies for Pr = 50. The red, yellow and blue lines are Gnielinski correlations for laminar, transitional and turbulent, respectively.

A. Heat transfer coefficients for $Pr = 50$

Figure. 5 shows dimensionless heat transfer coefficients compared to emperical correlations Eqs() and previous studies.

It is nessesary to estimate the maximum possible error in the parameters evaluated from the measuring data. Nusselt number is calcuretad from Equation 14.

$$Nu = \frac{\dot{m} c_p (T_1 - T_0)}{\lambda (T_w - T_1) d \pi L} \tag{14}$$

The uncertainty in Nusselt number is calcurated from Equation 15.

$$Nu = \sqrt{\sum \left(\frac{\partial Nu}{\partial X_i} \Delta X_i \right)^2} \tag{15}$$

Each parameter, X effects each parameters of Equation.14 Then, the mesurement uncertainty in Nusselt number leads to Equation 16.

$$\frac{\Delta Nu}{Nu} = \frac{1}{Nu}\sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta c_p}{c_p}\right)^2 + \left(\frac{\Delta \lambda}{\lambda}\right)^2 + \left(\frac{\Delta T}{T_0 - T_1}\right)^2 + \left(\frac{\Delta T (T_0 - T_w)}{(T_0 - T_1)(T_1 - T_w)}\right)^2 + \left(\frac{\Delta T}{T_1 - T_w}\right)^2} \tag{16}$$

B. *Friction coefficients for $Pr = 50$*

Figure. 6 shows friction coefficients compared to emperical correlations Eqs() and previous studies. It is obvious that the experimental results on friction coefficient for $2200 < Re < 7000$ are very well fitted by the citted correlation.

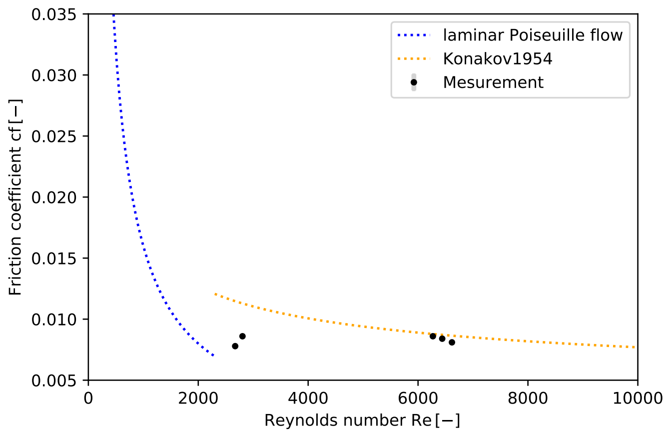

Fig. 6. Friction coefficients compared to literature data for Pr = 50. The red and blue lines are emperical correlations for laminar and turbulent flows, respectively.

C. *Purpose of the solution to deduce mesurement uncertainty for Nu*

Table II shows the orders of each terms in Equation 16. From this comprehensive result, temperature term is several orders of magnitude larger than others. Therefore, temperature mesurement is strongly inflected to mesurement uncertainty. According to this analisis, careful selections of temperature sensors are needed.

TABLE II
ODERS OF EACH TERMS IN EQUATION 16.

	Mass flow	Specific heat capacity	lambda	Temperature
Order	O (-8)	O (-8)	O(-8)	O(-4)

VII. FUTURE PLAN

VIII. APPENDIX

The experiment was carried out already existing fasilities by Christphan2018 [5]. Experimental procedure is as follows.

1) Switch on (Ein) Main switch (S0)
2) Start up a computer
   a) Select "Rohro.lvproj"
   b) Select Lab VIEW and click "Starten"
   c) Click "Nein"
   d) Select "Rohrpufsp.vi"
3) Prepare water supply for cooling experimental facilities.
   a) Open the tap water and save cool water in big tank.
   b) Cehck the temperature is approximately 15°C.
   c) Cehck the valves are in following state. Valve A is closed, B is opened, and C is closed.
   d) Turn on pump swith to supply cooling water
4) Check the value of mass flow rate on PC display and wait until the value is approximately 0.
5) Click T_s allec and T_s gleci to carry out Temperature calibration
6) Switch on heater (S1: Heizstab)
7) Click "Aushmine" to start the experiment
8) Set "Welder stom" under 300A
9) Switch on the pump (S4: Pump)
10) Switch on the welder
11) Adjest suitable experimental parameters for Re and Pr.
    a) Decrease Re and increase Pr
       Open valve A and close valve B little by little. Enhance cooling, statics viscosity increase. Thus, Pr increase.
    b) Decrease Re and decrease Pr
    c) Decrease Re and keeps Pr constant
12) Wait until the condition reaches steady
13) Click "Schreiben" to save the data
14) Switch of the Welder
15) Open the valves (flow max) and cool down the facilities
16) Wait until the facilities cool down enough
17) Turn off pump swith to stop supplying cooling water
18) Switch off the pump (S4: Pump)
19) Close the tap water
20) Click "close" for LabView application
21) Shut down PC and click "Klick sie heir unclear—-", not to download any current version

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