

Nusselt Number and Friction Factor Correlations for an Airflow in Polyvinyl Chloride (PVC) Circular Duct

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Abstract: An airflow in polyvinyl chloride (PVC) circular ducts is a common occurrence in many applications. However, the accurate prediction of the Nusselt number and friction factor for this type of duct is challenging due to the complex nature of the flow. This paper presents a new set of correlations for the Nusselt number and friction factor for airflow in PVC circular ducts. The new correlations are expected to be useful for the design and analysis of PVC circular ducts. They can also be used to improve the accuracy of numerical simulations of airflow in PVC ducts.

Keywords: Nusselt number, Friction factor, Correlations

1. Introduction

Nusselt number is the ratio of convection heat transfer to fluid conduction heat transfer under the same condition. It is an important parameter that can contribute to a better heat exchange rate. Moreover, the Nusselt number is equal to the dimensionless temperature gradient at the surface and measures the convection heat transfer occurring at the surface. Also, the Nusselt number is the function of the Reynolds and Prandtl number, which is related to the turbulent flow. Reynolds number is the ratio of inertial forces to viscous forces and the dimensionless number used to categorize the fluids systems in which the effect of viscosity is important in controlling the velocities of the flow pattern of a fluid. It is also used to determine whether a fluid is in laminar or turbulent flow, which is the number less than or equal to 2100 will be laminar flow while the turbulent flow will be greater than 2100. Hence, the Prandtl number is used to measure the ratio of the dominance of velocity or hydrodynamic boundary layer over the thermal boundary layer. Over than that, it is related to the friction factor. It will be defined in terms of the pressure drop and the air mass velocity. The friction factor is related to the Reynolds number by a set of correlations and depends on whether the flow regime is laminar, transitional, or turbulent.

Correlation is a statistical measure that expresses the extent to which two variables are linearly related. Based on previous research, the correlations are developed based on the results of available series solutions for four fundamental boundary conditions. The correlations use exponential, and power law functions for dimensionless axial and radial lengths. The four primary boundary conditions are first-kind, second-kind, third-kind, and fourth-kind of boundary conditions. Hence, the new correlations accurately predict the local Nusselt numbers for all studied flow regimes and boundary conditions. The important of Nusselt number is used to determine whether the heat is conduction or convection and is also a non-dimensional heat transfer coefficient. While the friction factor is an important dimensionless parameter for fluid flow through rock fractures that relates pressure head loss to average flow velocity, it can be affected by both fracture geometry and flow regime.

Based on observations and investigations, it has been determined that there is an issue with the correlation between the Nusselt number and friction factor, which is to find a suitable correlation that is simple, accurate, and easy to use.

2. Correlation of Nusselt Number and Friction Factor

Nusselt has found a solution to the problem of determining the heat transfer rate for a horizontal cylinder and a vertical plane surface with uniform surface temperatures when the condensate flow is laminar and only controlled by gravity and viscous forces. The main assumptions of Nusselt are that heat transfer across the condensate film occurs purely through conduction, that vapour drag has little impact on stabilising the falling condensate film, and that the properties of the condensate are uniform across the film and essentially independent of temperature [1-3].

2.1 Dittus Boelter Correlation

Dittus-Boelter correlations are the most widely quoted and used heat transfer for turbulent flow in ducts. The Dittus-Boelter equation is shown below. The Dittus-Boelter equation is an explicit function for calculating the Nusselt number, especially for turbulent flow. The Nusselt number is the ratio of convective to conductive heat transfer across the boundary. The Dittus-Boelter correlation may be used for small to moderate temperature differences, $T_{wall} - T_{avg}$, with all properties evaluated at an average temperature, T_{avg} . The Dittus-Boelter correlation is used to calculate the surface coefficient of heat transfer for fluids in turbulent flow inside clean and round pipes. The Nusselt number combines the Reynolds number and the Prandtl number; therefore, it combines many variables [4].

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (1)$$

2.2 Colebrook Correlation

Based on Praks & Brkic [5], the empirical Colebrook equation from 1939 is still accepted as an informal standard way to calculate the friction factor of turbulent flows ($4000 < Re < 10^8$) through pipes with roughness between negligible relative roughness ($\varepsilon/D \rightarrow 0$) to very rough. The Colebrook equations include the flow friction factor, λ in an implicit logarithmic form, λ being a function of Reynolds number, Re , and the relative roughness of the inner pipe surface. Many available explicit approximations to evaluate the error introduced by the Colebrook equation. It is necessary to determine the value of the friction factor, λ , from the Colebrook equation as accurately as possible. The most accurate way to achieve that is by using the iterative method. The most iterative approach is the simple fixed-point method does not require derivatives of the Colebrook function, while the three-point iterative methods require only 1 to 3 iterations to achieve the level of accuracy.

The empirical Colebrook equation is in common use to evaluate flow resistance in turbulent flow through rough or smooth pipes.

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left(\frac{2.51}{Re \sqrt{\lambda}} + \left(\varepsilon / 3.7D \right) \right) \quad (2)$$

In the Colebrook equation, λ represents Darcy flow friction factor, Re Reynolds number, and ε/D relative roughness of inner pipe surfaces. The Colebrook function relates the unknown flow friction factor λ as a function of itself, the Reynolds number Re , and the relative roughness of inner pipe surface ε/D , $\lambda = f(\lambda, Re, \varepsilon/D)$. It is valid for $4000 < Re < 10^8$ and $0 < \varepsilon/D < 0.05$. The Colebrook equation is transcendental and thus cannot be solved in terms of elementary functions [6].

3. Materials and Method

The materials and methods section, otherwise known as methodology, describes all the necessary information that is required to obtain the results of the study.

3.1 Design of local exhaust ventilation system

LEV is the system that captures dust, vapours, and fumes. The system will operate at the maximum of 1488 RPM. The 2 litre of boiled water will be placed at the hood of the system. Thermocouple is placed at five different point of the duct. There are three different type of filter box which is no filter, HEPA filter and atomizer. The LEV system included the capture hood, motor, centrifugal fan, filter box, and fan outlet.

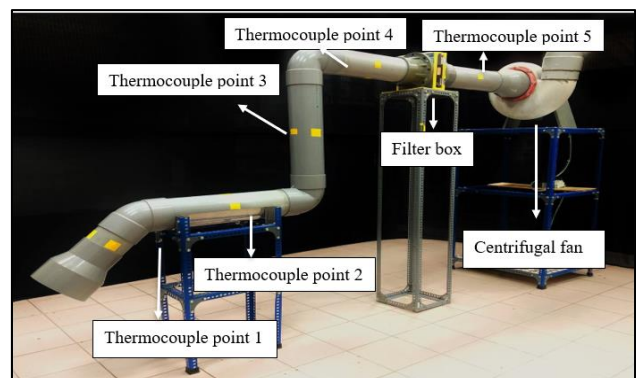


Fig. 1 – Local exhaust ventilation system

3.2 Method for experimental work

The water vapour from boiled water is used to obtain the value of temperature at every five different points of the Local Exhaust Ventilation System. The water vapour circulates in the Local Exhaust Ventilation System and the thermocouple was placed at every five different point. The data is recorded by using a data logger from Pico Log. The fan speed was adjusted to provide the necessary airflow inside the system. From the obtained temperature, the value of Prandtl number, density and dynamic viscosity will be calculated by using interpolation method. The Reynold number will be calculated by using the formula and substitute the information gathered into it.

3.3 Equations for Nusselt number

According to the G. Smaism [7], the Nusselt number has been found to increase as the Reynolds number and volume fraction increases. This is due to two factors. First, as the volume concentration higher, nanofluid's thermal conductivity will be higher along with it, increasing the number of particles and consequently, their total contact area. This resulted in a more efficient heat exchange between the nanoparticles and base fluid. Secondly, when flow rates for nanofluids high, the Reynolds number and the heat transfer also high. Hence, below is the empirical equations that calculate the Nusselt number.

$$Nu = 0.027 Re^{0.8} Pr^{0.4} [8] \quad (3)$$

$$Nu = 0.021 Re^{0.8} Pr^{0.5} [9] \quad (4)$$

$$Nu = 0.085 Re^{0.71} Pr^{0.35} [10] \quad (5)$$

The validation is done in two stages. First, the numerical results of heat transfer in a smooth channel are compared with the empirical correlations and experimental of the previous study. Next, the simulations reproduce the thermal and friction enhancement caused by a trapezoidal winglet. For turbulent flow conditions, smooth channels can be described by the correlations given below for the Nusselt number [5]:

$$Nu = 0.0214 (Re^{0.8} - 100) Pr^{0.4} [11] \quad (6)$$

Moreover, according to Saini et. al. [12], the validity of the experimental setup to verify the values of the Nusselt number and friction factor were compared with the values obtained from correlations available in the literature for smooth duct, namely the Dittus-Boelter equation and modified Blasius equation. The Nusselt number for a smooth rectangular duct is given by the Dittus-Boelter equation as in Eqns. (1).

3.4 Equations for friction factor

According to the Ramadhan [13] stream is assumed to be stable, incompressible, Newtonian fluid, and turbulent with a constant thermos physical nature of nano-fluid, no gravitational effects and heat conduction in the axial direction. For dynamic equality conditions for two media streams, nano-particles and base fluid in the tubes, the friction factor can be written as follows [14].

$$f_{Bl} = \frac{0.3164}{Re^{0.25}} \quad (7)$$

Based on Taler [15], although the explicit formulas of Blasius, Moody and Allene & Eckert for the friction factor in the smooth tube turbulent flow are straightforward, they can only be applied in certain Reynolds number range. Below are the correlations that stated in this paper.

$$f = \frac{0.184}{Re^{0.2}} [16] \quad (8)$$

$$f = 0.00556 + \frac{0.432}{Re^{0.308}} [17] \quad (9)$$

$$f = \frac{1}{(1.7765 \log Re - 1.4053)^2} [15] \quad (10)$$

$$f = \frac{1}{(1.2776 \log Re - 0.406)^{2.246}} [18] \quad (11)$$

$$f = 0.85 Re^{-0.25} [12] \quad (12)$$

4. Results and Discussion

The water vapour from boiled water is used to obtain the value of temperature at every five different point of the Local Exhaust Ventilation System. The water vapour circulates in the Local Exhaust Ventilation System and the thermocouple were placed at every five different point. The data is recorded by using data logger from Pico Log. The fan speed was adjusted to provide the necessary airflow inside the system. From the obtained temperature, the value of Prandtl number, density and dynamic viscosity will be calculated by using interpolation method. The Reynold number will be calculated by using the formula and substitute the information gathered into it.

4.1 Nusselt number

Table 1 shows the result of Nusselt number that been calculated by using correlations been proposed from six different author and mentioned above. Dittus Boelter was the main formula to be compared with the other six correlations. The percentage of error was also calculated to determine which correlation is less error compared to Dittus Boelter correlation. As stated in the table below, the percentage error for Saini is 4.35% which is low percentage error. While the high percentage error from Maiga's correlation which is 55.68%.

Table 1 – The result of Nusselt number

RPM	[4]	[11]	[12]	[8]	[9]	[10]	[15]
500	38.7	34.2	40.4	45.4	34.1	62.2	47.6
700	39.6	35.0	41.3	46.5	35.0	63.4	48.5
900	50.1	44.8	52.3	58.8	44.2	78.1	59.3
1100	56.1	50.3	58.4	65.8	49.4	86.3	65.2
1300	62.9	56.4	65.7	73.9	55.5	95.7	72.0
1488	53.3	47.8	55.6	62.6	47.0	82.5	62.5
Total	300	268	313	353	2.2	468	355
Error (%)		10.7	4.4	17.3	11.8	55.7	18.1

Figure 2 shows the graph of Nusselt number, Nu against Speed, n (RPM) for the atomizer. The graph pattern shows an increasing pattern in the speed of 500 RPM until 1300 RPM and the value dropped at the speed of 1488 RPM. This pattern may occur because of the air circulation inside the PVC pipe. The Nusselt number increases as the speed increases. However, the rate of increase is not constant. At low speed, the Nusselt number increases rapidly with increasing speed. Hence, at high speed the Nusselt number decreases slightly. According to M. Vadivelu [19], the higher the Nusselt number, the higher the speed and resulting to lower values of convective resistance [20].

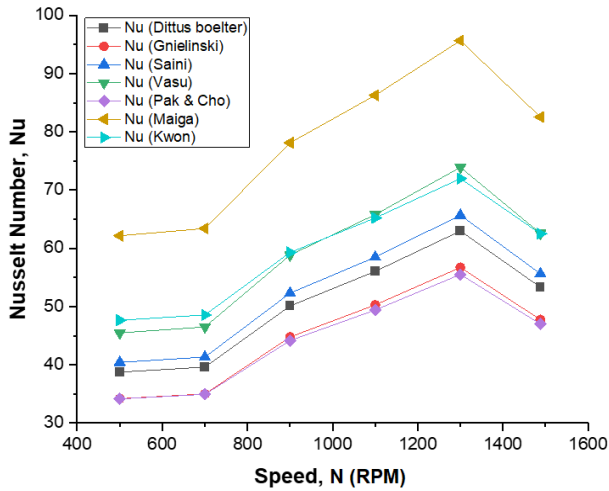


Fig. 2 – Nusselt number, Nu against Speed, n (RPM)

4.2 Friction factor

Table 2 shows the result of friction factor that been calculated by using correlations been proposed from six different author and mentioned above. Colebrook was the main formula to be compared with the other six correlations. The percentage of error was also calculated to determine which correlation is less error compared to Colebrook correlation. As mentioned in the table below, the percentage error for Saini is 175.85% which is a high percentage error. While the low percentage error from Taler's correlation which is 0.11%.

Table 2 – The result of Friction factor

RPM	[5]	[12]	[8]	[7]	[17]	[15]	[18]
500	0.029	0.080	0.030	0.028	0.029	0.029	0.029
700	0.029	0.079	0.030	0.028	0.029	0.029	0.029
900	0.027	0.074	0.027	0.026	0.027	0.026	0.027
1100	0.026	0.071	0.026	0.025	0.026	0.026	0.026
1300	0.025	0.069	0.026	0.025	0.025	0.025	0.025
1488	0.026	0.072	0.027	0.026	0.026	0.026	0.026
Total	0.161	0.445	0.166	0.157	0.162	0.160	0.161
Error (%)		175.9	2.68	2.76	0.33	0.67	0.11

Figure 3 shows the graph of Friction factor, f against Speed, n (RPM) for the atomizer. The graph pattern shows a slightly decreasing pattern. This pattern may occur because of the small range of temperature obtained and resulting to low Prandtl number. For turbulent flow, the friction factor is relatively independent of speed. Hence, it leads to friction factor remains relatively constant within a certain range of Reynolds number. According to Raeymaekers [20], the decreasing of friction factor as the increasing speed may be due to the formation of air. Hence, in this experiment, water vapour from the boiled water was circulate in the PVC pipe and met the atomizer in the middle may be the factor of unstable result. Figure 4 shows the maximized line graph from the figure 3.

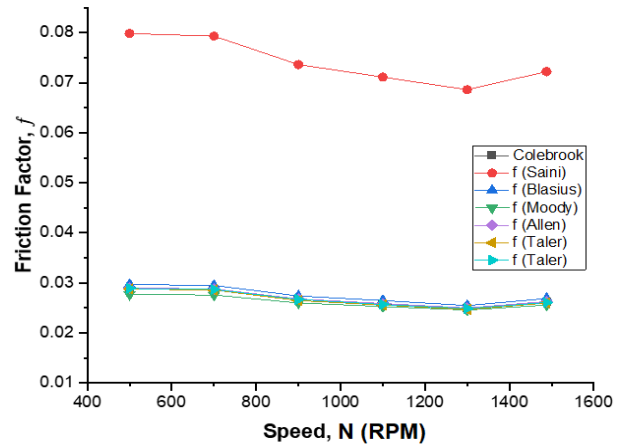


Fig. 3 – Friction factor, f against Speed, n (RPM)

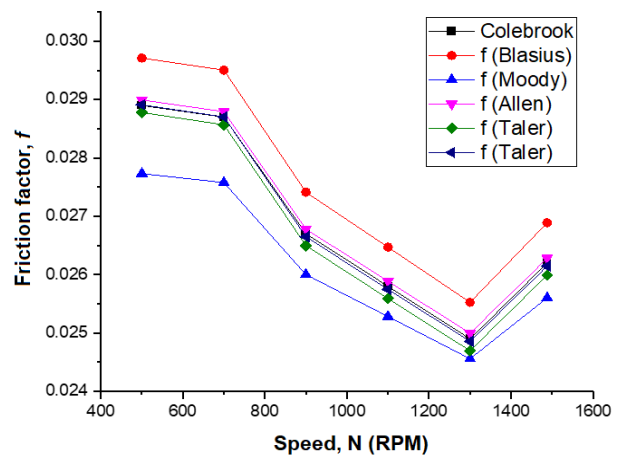


Fig. 4 – Friction factor, f against Speed, n (RPM) without Saini's correlation

5. Conclusion

From the work, it can be concluded that there is suitable correlation should be proposed for both Nusselt number and friction factor. Low percentage error for Nusselt number is 4.35% which is the correlation from the author's Saini. While the low percentage error for friction factor is 0.11% from the Taler's equation. Hence, other than Dittus Boelter and Colebrook equation, we can take into consideration to use the two mentioned correlations above.

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