Heat Transfer and Pressure Drop in Transitional Flow: A Short Review

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Abstract. In the present work, an effort has been made to present the short review of all the numerical as well as experimental studies done in the field of heat transfer and pressure drop in the transitional flow regime. The experimental and numerical studies on transition flow are reported. Though, there are several challenges to do experiments in transition flow regime. Various techniques are also discussed and summarized. Results show that the techniques prove outstanding performance, but few methods quiet suffer from high pressure drop. As per discussion, new viewpoints on the current research gaps and future research ways have been providing for the development of heat transfer techniques.

1. Introduction
Energy conservation is one of the biggest tasks of today’s growing world. With the advancement in technology, the consumption of energy is also kept increasing at a very rapid rate. This grows the need for the development of such devices which can work energy efficiently. One such device is a heat exchanger (HE). HE is used for the exchange of energy between two or more fluids. Some examples of HEs are radiators of car engines, evaporators, condensers, air preheater, cooling towers, etc. To obtain maximum effectiveness, the optimization of design parameters is required. While designing the HEs, engineers focussed on high heat transfer rate and low friction factor coefficient. In the laminar flow regime, the pressure drops as well as the heat transfer rate both are low [1-4] while in turbulent flow both pressures drop, and the heat transfer rate is very high [5-20]. This problem made researchers focus on the transitional flow regime. But this regime has its problem of unstable and chaotic flow due to which it is advised to avoid designing of HEs in this regime.

The transitional flow regime was first studied in detail by Ghajar and his Co-workers [21-27]. Following the path of Ghajar, Meyer with co-workers also starts working on the transitional flow regime [28-34]. These two professors along with their co-workers shed light on the pros and cons of working in the transitional flow regime. Beside this a very few manuscripts are available on the heat transfer and pressure drop in the transitional flow regime.

In the present work, an effort has been made to present the short review of all the numerical as well as experimental studies done in the field of heat transfer and pressure drop in the transitional flow regime.

2. History of Transitional Flow
The transitional flow regime is defined as the flow regime when fluid flow transformed from a laminar regime to the turbulent flow regime. Generally, it occurred anywhere between Reynolds
number (Re) of $2.3 \times 10^3$ to $10 \times 10^3$ [21]. Before 1990, very few authors discussed the transition regime in a very specific manner for heat transfer. In the year 1965, Unterberg and Edwards [36] first mentioned transitional flow in film evaporation of falling saline water on the vertical surface under the influence of gravity. Mceligot et al. [37] studied the heat transfer and wall friction in the circular channel for air, nitrogen, and helium for Re range between 3 000 – 10 000. A correlation was presented by Petersen and Christiansen [38] to predict the heat transport for pseudo plastic and Bingham fluids in the transitional regime. The developed correlations are in good agreement with a standard deviation of 17.7% for the complex transitional flow regime. Inayatov [39] experimentally investigated the heat transfer for Re 1 000 – 12 000 for water as working fluid externally flows over multiple copper tubes. Humphreys and Welty [40] experimentally investigated the free convection heat transfer in laminar and transitional regime in the vertical heated channel for mercury and developed a correlation for Nusselt Number (Nu) prediction which can be used for all values of Grashof numbers (Gr). Jaster and Kosky [41] perform experiments to predict the condensation heat transfer in the transitional flow regime. A correlation for predicting the transition Nusselt number is also developed.

3. Pressure Drop in Transitional Flow Regime

The year 1992 acts as the turning point in the history of thermo-hydraulics in the transitional regime. For the first time, the heat transfer and pressure drop were studied in detail. The main credit for this goes to Ghajar and co-workers whose research work in transitional zone helps in a better understanding of the heat transfer and pressure drop. Ghajar and Madon [21] experimentally investigated the pressure drop in the transition regime for re-entrant, square-edged, and bell-mouth inlets. The schematic of the experimental setup used for the investigation is shown in Fig. 1. Two different working fluids such as distilled water and ethylene glycol are used in different concentration. The Re is varied between 500 – 15 000. The results obtained from 114 experimental runs revealed that transition for (i) Re-entrant inlet started around Re of 1980 and ends at 2125, (ii) square-edged inlet starts at 2070 and ends at 2840, while (iii) for bell-mouth, the transition occurs at 2125 and terminates at 3200. Second-order polynomial correlation for predicting fully developed skin friction was developed using the data for all the three geometries of the inlet. In another work, Tam and Ghajar [23] experimentally investigated the pressure drop in the fully developed flow in a horizontal circular pipe with different inlet geometries under isothermal as well as non-isothermal conditions. Ethylene Glycol along with water is used as the working fluid with Re range between 1 000 – 17 000 to cover all the flow regimes. The data obtained from the investigation shows enhancement in friction coefficient with an increase in heat flux at fixed Re because of the presence of secondary flow which increases the lower and upper limits of isothermal boundaries. In another investigation, Tam et al. [27] investigated the impact of horizontal tube inlet geometries on the friction factor in the transitional flow regime. Ethylene Glycol and water mixture have been used as working fluid. The range of Reynolds number was varied from 800 to 22 000. It was found that the increase in the heating condition significantly affects the friction factor. Meyer et al. [28] investigated the pressure drop in the transitional flow for four different inlet geometries. Water is taken as the working fluid with Re range between 1 000 – 20 000. The result obtained for the adiabatic friction factor shows the transition in re-entrant type inlet started at Re = 2 100 while for bell-mouth entrance transition is delayed up to Re = 7 000. From the above obtained results, the author concluded that smoother entrance led to delayed transition while for diabatic pressure drop, inlet geometry shows no dependence. In another assessment by Meyer and Olivier [29], the pressure drop was investigated in transition regime for enhanced tube as shown in Fig. 2 for developing and developed flow and developed correlations to predict the critical value of Re. It was
revealed from the experimental data that transition in enhanced tube started at lower Re when compared with a smooth tube. Ndenguma et al. [30] experimentally investigated the pressure drop in the transitional flow regime for mixed convective heat transfer in four annular passage of different diameters and developed correlations to predict the friction factor. The schematic representation of the test setup is shown in Fig. 3. Water was taken as working fluid with Re varied from 100 to 10,000. This investigation revealed that the friction factor depends on the geometrical parameters of the test section. The larger the annular gap, the higher will be the friction factor for a fixed Re.

Dobrnjac [42] conducted a study to develop an efficient formula to predict the friction factor coefficient in the transitional flow regime. Based on digitalized Nikuradse’s measurements, an analytical expression was developed to predict the friction factor for the Re range from 0 to $10^6$. Ishida and Tsukahara [43] numerically investigated the annular Poiseuille flows in a transitional regime for friction factor. The frictional Reynolds number, $Re$, considered for the assessment range between 48 - 150. Given the state of turbulent-laminar coexistence, the findings revealed that the helical turbulence contributed to the friction coefficient being as high as the fully turbulent data. All the above research works are summarized in Table 1.
### Table 1. Summary of Research work related to Pressure drop in Transitional Regime.

| Author’s Name | Year of Publishing | Range of Reynold’s Number | Summary of Research Work | Key Outcomes |
|---------------|--------------------|----------------------------|--------------------------|--------------|
| Ghajar and Madon [21] | 1992 | 500-15000 | Experimentally investigated the pressure drop in the transition regime for re-entrant, square-edged, and bell-mouth inlets. | Transition for (i) Re-entrant inlet started around Re of 1980 and ends at 2125, (ii) square-edged inlet starts at 2070 and ends at 2840, while (iii) for bell-mouth, the transition occurs at 2125 and terminates at 3200. |
| Tam and Ghajar [23] | 1997 | 1000-17000 | Experimentally investigated the pressure drop in the fully developed flow in a horizontal circular pipe with different inlet geometries under isothermal as well as non-isothermal conditions. | Enhancement in friction coefficient with an increase in heat flux at fixed Re because of the presence of secondary flow which increases the lower and upper limits of isothermal boundaries. |
| Ghajar et al. [25] | 2008 | 500-10000 | Experimentally revealed the impact of single-phase transitional flow on the friction factor in mini and microchannels. | The friction factor has a very little variation for the diameter range between 2083 μm and 1372 μm while further decreasing the diameter shows a significant change in the friction factor profile. |
| Ghajar et al. [26] | 2010 | 500-10000 | Experimental assessment to investigate the pressure drop in transitional flow for 12 stainless steel microtube with a diameter range between 2083 μm and 337 μm. | The results show negligible influence on the friction factor for tubes with a diameter range between 2083 μm and 1372 μm. Below 1372 μm significant change in friction factor water noticed. |
| Tam et al. [27] | 2013 | 800-22000 | The impact of horizontal tube inlet geometries on the friction factor in the transitional flow regime. | It was found that the increase in the heating condition significantly affects the friction factor. |
| Meyer et al. [28] | 2009 | 1000-20000 | The pressure drop in the transitional flow for four different inlet geometries. | Smoother entrance led to delayed transition while for diabatic pressure drop, inlet geometry shows no dependence. |
| Meyer and Olivier [29] | 2011 | 500-13000 | The pressure drop was investigated in transition regime for enhanced tube | Transition in enhanced tube started at lower Re when compared with a smooth tube. |
| Ndenguma et al. [30] | 2017 | 100-10000 | The pressure drop in the transitional flow regime for | The friction factor depends on the geometrical |
mixed convective heat transfer in four annular passage of different diameters and developed correlations to predict the friction factor. Study to develop an efficient formula to predict the friction factor coefficient in the transitional flow regime. Numerically investigated the annular Poiseuille flows in a transitional regime for friction factor.

4. Heat Transfer in Transitional Flow Regime

Heat transfer in transition flow regime is also very important like pressure drop. Ghajar and Tam [22] experimentally investigated thermal transport in the transition regime for three inlet geometries. Distilled water and ethylene glycol in different concentrations were used as working fluid for Re range between 280 – 49 000. Other parameters used for the study are Prandtl Number (4 -158), and Grashof Number (1 000 - 2.5×10^5). It was found that transitional Re for Re-entrant range between 2 000 – 8 500, square-edged range between 2 400 – 8 800, and bell mouth range between 3 800 – 10 500.

Meyer and Olivier [31] experimentally reveal the heat transfer in the transitional flow regime for modern chiller plants with different inlet configurations. A tube in tube counter flow heat exchanger was used as an experimental setup with water as the working fluid. Hot fluid at 40°- 45° flows in the inner tube while cold fluid at 20° flows in the outer tube of the heat exchanger. It was found that heat transfer in the chiller plant remains uninfluenced of inlet geometries for the horizontal plain tube. In another investigation the heat transfer for enhanced tubes in the transitional flow regime and developed the correlation for predicting the heat transfer in the transitional flow regime [32]. The data obtained for heat transfer shows an overall enhancement in heat transfer when compared with the smooth tube.

Everts and Meyer [33] experimentally investigated the heat transfer in developing and developed flow in the transitional regime for two horizontal circular tubes of diameter 4 mm and 11.5 mm at constant heat flux. The heat transfer is measured for Re range between 700 – 10 000. It was found that the effect of free convection in the flow field reduces the range of transitional flow for all the Re. Osman et al. [34] investigated convective heat transfer in transitional flow for Alumina-water nanofluid of different concentrations in a rectangular channel. The range of Re taken for investigation varied from 200 to 7 000. The data obtained after investigation shows enhancement in heat transfer coefficient for all volume concentrations with maximum heat transfer coefficient for 1% volume concentration. Convective heat transfer efficiency was also found to be better in the transitional flow regime when compared with the other two regimes.

García et al. [44] experimentally revealed the augmentation of heat transfer in Laminar-transitional-turbulent flow regimes for a tube with wire coil inserts for different values of Prandtl number (Pr). Water with Propylene Glycol was taken as working fluid with Re varied from 80 to 90 000 and Pr between 2.8 to 150. Six wire coils with different p/D and e/D were used for the experimentation. It was revealed from the experimental investigation that heat transfer was enhanced by 200% in the transitional flow regime while the pumping power remains constant. This investigation shows that wire coils perform best in the transitional regime. A similar investigation with a different value of pitch for wire coil inserts with Re varied between 10 to 2 500 and Pr varied between 200 to 700 was
also reported [45]. The results obtained from the investigation show eight times enhancement in heat transfer when compared with the smooth tube. Martínez et al. [46] investigated the heat transfer augmentation for Newtonian and non-Newtonian fluid in viscous and transitional flow regimes. The test section consists of a tube with an inner diameter of 18 mm fitted with stainless steel wire coils having $p/D$ of 1 and 2, $e/D$ of 0.09. The range of Re was taken between 10 and 1 300. It was found that at low Re wire coil shows results similar to a plain tube. Peixinho et al. [47] conducted an experimental assessment to investigate the heat transfer in the transitional flow regime. Three working fluids namely, glucose syrup, 2% CMC, and 0.2% Carbopol have used for the investigation. It was found that the heat transfer coefficient is increased in the transitional flow regime due to the disturbed thermal boundary layer. Bertsche et al. [48] experimentally investigated the laminar, transition, and turbulent flow regime for thermal transport in the circular pipe. The Reynolds number used for the study varied from 500 to 23 000 while Pr varied from 7 to 41. The data obtained from the investigation are in good agreement with Gnielinski’s calculation for all value of Pr. It was found that transitional flow occurs between 2 300 to 4 000 of Re. Sarmiento et al. [49] proposed a new model to predict Nu for circular as well as non-circular tubes. This model is valid for Pr range from 0.7 to 78 and Re range for 890 and 2 48 800. The proposed model is in good agreement with other proposed correlations with a square mean error of 10%.

**Table 2. Summary of Heat Transfer in Transitional Flow Regime.**

| Author’s Name          | Year of Publishing | Range of Reynold’s Number | Summary of Research Work                                                                 | Key Outcomes                                                                 |
|------------------------|--------------------|----------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Ghajar and Tam [22]    | 1994               | 280-49000                  | Thermal transport in the transition regime for three inlet geometries.                    | Transitional Re for Re-entrant range between 2000-8500, square-edged range    |
|                        |                    |                            |                                                                                          | between 2400-8800, and bell mouth range between 3800-10,500.                  |
| Tam and Ghajar [24]    | 2006               | -                          | The heat transfer in the transitional flow regime in a horizontal pipe for three different| Presented a flow regime map to differentiate between the boundary for forced and mixed convection in a horizontal plain tube. |
|                        |                    |                            | inlet geometries under uniform heat flux conditions.                                      |                                                                               |
| Meyer and Olivier [31] | 2011               | 1000-15000                 | The heat transfer in the transitional flow regime for modern chiller plants with different | Heat transfer in the chiller plant remains uninfluenced of inlet geometries for the horizontal plain tube. |
|                        |                    |                            | inlet configurations.                                                                    |                                                                               |
| Meyer and Olivier [32] | 2011               | 3000-20,000                | The heat transfer for enhanced tubes in the transitional flow regime and developed the    | An overall enhancement in heat transfer when compared with the smooth tube.     |
|                        |                    |                            | correlation for predicting the heat transfer in the transitional flow regime.              |                                                                               |
| Everts and Meyer [33]  | 2018               | 700-10000                  | The heat transfer in developing and developed flow in the transitional regime for two     | The effect of free convection in the flow field reduces the range of transitional flow for all the Re. |
|                        |                    |                            | horizontal                                                                                          |                                                                               |
| Author(s)            | Year | Range   | Description                                                                                                                                 |
|----------------------|------|---------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Osman et al. [34]    | 2019 | 200-7000| Convective heat transfer in transitional flow for Alumina-water nanofluid of different concentrations in a rectangular channel.            |
| Garcia et al. [44]   | 2005 | 80-90000| The augmentation of heat transfer in Laminar-transitional-turbulent flow regimes for a tube with wire coil inserts for different values of Prandtl number (Pr). |
| Garcia et al. [45]   | 2007 | 10-2500 | The augmentation of heat transfer with a different value of pitch for wire coil inserts with Re varied between 10 to 2500 and Pr varied between 200 to 700. |
| Martínez et al. [46] | 2014 | 10-1300 | The heat transfer augmentation for Newtonian and non-newtonian fluid in viscous and transitional flow regimes.                               |
| Peixinho et al. [47] | 2008 | 100-10000| The heat transfer in the transitional flow regime.                                                                                           |
| Bertsche et al. [48] | 2016 | 500-23000| Experimentally investigated the laminar, transition, and turbulent flow regime for thermal transport in the circular pipe.                |
| Sarmiento et al. [49]| 2020 | 890-248800| A new model to predict Nu for circular as well as non-circular tubes.                                                                       |

5 CONCLUSIONS
In the present work, an effort has been made to present the short review of all the numerical as well as experimental studies done in the field of heat transfer and pressure drop in the transitional flow regime. Though, according to literature it is found that there are several challenges to do experiments in transition flow regime. Various transition techniques are also discussed and summarized. After the current short review, it can be established that the transition regime width changes according to the tube geometry, rate of heating, working fluid etc. It is also found that the geometrical parameters of
inserts like twist ratio, length, spring ratio, inlet disturbances, roughness height, width, etc. affect the HT augmentation considerably in transitional flow regime (TFR). So, the bottom line of the study is that the transition flow regime is quite young research field and it is important to study more on this field.

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