# A new perspective on forced and mixed convection heat transfer in the laminar and transitional flow regimes

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**ABSTRACT**
One of the most important internal heat transfer problems is laminar convection heat transfer through a smooth circular tube. Depending on the method of heating/cooling (constant heat flux or constant wall temperature) the flow regimes might be forced convection or mixed convection. This will significantly influence parameters such as the development of the hydrodynamic and thermal boundary layers and entrance lengths, the local- and average heat transfer coefficients, as well as the local and average pressure drops.

Especially for forced convection conditions, numerous theoretical work was done from which the above mentioned parameters were estimated. Unfortunately, not a lot of rigorous experimental work was conducted to verify these parameters. Furthermore, only a little experimental and theoretical work has been done for mixed convection heat transfer. It should also be noted that most of the works were conducted for the laminar flow regime and very little work has been done for the transitional flow regime.

It was therefore the purpose of this study to give a new perspective on forced and mixed convection heat transfer in smooth circular tubes by conducting rigorous experiments and compiling an experimental database which were orders of magnitude larger than previous databases. Experiments were conducted on tube diameters of 4 mm, 5.1 mm and 11.5 mm, with lengths of 6 m, 4.6 m and 9.5 m respectively. A total of 2 185 mass flow rate measurements, 165 964 temperature measurements and 4 045 pressure drop measurements were obtained between Reynolds numbers of 500 and 10 000 and the Prandtl number and Grashof number ranges were 3-7 and 30-2.49×$10^5$. Varying Grashof numbers from 62 to 2.44×$10^3$ were obtained by changing the tube inclination angle from -90° to +90° and proofing that forced convection conditions can be achieved for vertical upward and downward flow conditions if the Reynolds numbers were larger than approximately 600. The Grashof number was further increased by increasing the heat flux and tube diameter

From the experimental results eight new perspectives were developed which can be categorized under:
Forced convection laminar

1. A new correlation that can be used to accurately determine the thermal entrance length for simultaneously hydrodynamically and thermally developing flow. This correlation shows that the well-known equation of $L_t = 0.05RePr$ is correct for hydrodynamically fully developed flow at the inlet of the test section. However, a longer thermal entrance length is required if the flow is simultaneously hydrodynamically and thermally developing, therefore a coefficient of 0.12 was suggested.
2. The fully developed forced convection laminar Nusselt number is not constant at 4.36, but is a function of Reynolds number for Reynolds numbers greater than 600. Therefore, a revised forced convection Nusselt number correlation was developed.

Mixed convection laminar

1. Three different regions (Forced Convection Developing, Mixed Convection Developing and Fully Developed) with unique heat transfer characteristics were identified and quantified.
2. Free convection effects were found to decrease the thermal entrance length, therefore a new correlation to accurately determine the thermal entrance length for mixed convection conditions was developed.

Forced convection transition

1. The width of the transitional flow regime decreased and the transition gradient increased as the flow developed along the tube length. Once the flow was fully developed, both the width of the transitional flow regime and transition gradient remained constant.

Mixed convection transition

1. Free convection effects caused the width of the transitional flow regime to decrease and the transition gradient to increase. At very high Grashof numbers, the transitional flow regime even became negligible and the flow regime changed from the laminar flow regime to the quasi-turbulent flow regime at the next Reynolds number increment.
2. The start of transition occurred at the same moment in time along the entire test section, however, the critical Reynolds numbers increased along the test section due to the changes in fluid properties with temperature. The end of transition occurred earlier as the flow develop along the tube length.
3. Free convection effects caused transition to occur earlier (at lower mass flow rates), however, the critical Reynolds numbers increased due to the changes in fluid properties with temperature.