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Advantages and Limitations of Uniform Wall Temperature Experimental and Numerical Investigations

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Abstract - This study critically compares the advantages and limitations of experimental and numerical investigations of laminar internal flow with a uniform wall temperature (UWT) boundary condition using two representative case studies. A review of the experimental setups, computational domains, and validation outcomes provides the necessary foundation for this comparison. While experimental investigations provide direct measurements that capture complex flow behaviours and ensure physically realistic results for the essential validation of numerical models, they are constrained by limited spatial resolution, measurement uncertainties, and high time and cost requirements, thereby restricting their suitability for parametric investigations. Furthermore, experimental investigations are limited by their inability to measure or visualise certain parameters directly. Conversely, numerical investigations enable the extraction and visualisation of any parameter at any location in the flow domain, support efficient, cost-effective and accurate parametric studies, and allow for the isolated quantitative investigations of underlying flow and heat transfer mechanisms, facilitating the identification of discrepancies. The limitations of numerical investigations, however, include reliance on simplifying assumptions and strong dependence on detailed experimental data and setup specifications for validation. Acknowledging the strengths and weaknesses of both methods, it is concluded that an integrated numerical and experimental approach would enable efficient resource allocation by limiting experimental investigations to critical cases within the parameter space—such as those involving complex physical phenomena or parameter extremes—while employing numerical simulations to populate the broader parameter space with high-resolution data that do not include measurement uncertainties. This combined approach mitigates the limitations of each method and leverages their respective advantages, thereby deepening the understanding of both numerical and experimental results, enhancing accuracy, refining empirical correlations, and ensuring that results remain grounded in real-world physical behaviour.

Keywords: Experimental, numerical, uniform wall temperature, heat transfer, laminar flow, single-phase

1. INTRODUCTION

Heat exchangers are essential components in numerous industrial applications, playing a major role in both energy generation and use. The thermal condition at the solid-fluid interface in heat exchangers is typically idealised using one of two boundary conditions, one of which is the uniform wall temperature (UWT) boundary condition. Battery thermal management systems are one application of laminar UWT heat exchange [1], which has gained immense traction in recent years due to the increasing demand for high-performance lithium-ion batteries in electric vehicles and energy storage systems. To facilitate heat exchanger optimisation, both experimental and numerical studies are employed to develop accurate correlations, conduct parametric investigations, and generate insights applicable to practical designs. Consequently, extensive research on laminar UWT flow through circular tubes has been conducted using experimental [2-5], numerical [6-8], and analytical [9-12] approaches. However, analytical studies are heavily constrained by simplifying assumptions, with most existing works assuming constant fluid properties and only one [11] addressing mixed convection. The scarcity of analytical studies in mixed convective flow arises from their reliance on restrictive assumptions, which limit their applicability to a narrow range of conditions. Furthermore, most analytical solutions for UWT laminar flow have already been established, and extending this approach to more complex scenarios becomes increasingly difficult compared to experimental and numerical methods.

Experimental research has predominantly focused on average Nusselt numbers, with only a few [2, 4] focusing on the local Nusselt numbers. Notably, Yousef and Tarasuk [4] provided only sparse local Nusselt number data, accompanied by significant uncertainties. The first comprehensive experimental investigation of local mixed convective Nusselt numbers was conducted by Coetzee et al. [2], who also examined wall temperature uniformities and local Grashof numbers. In contrast, numerical forced and mixed convection studies [6-8] have largely focused on local Nusselt numbers, temperature profiles and velocity profiles. Steyn et al. [6] was the first numerical mixed convective study to quantitatively assess free convection effects, by calculating the strength of buoyancy-driven secondary flow, and the development of the hydrodynamic and thermal boundary layers.

Both experimental and numerical studies contribute significantly to the field, with their effectiveness contingent upon the specific research objectives. Experimental studies offer direct measurements that reflect real-world phenomena, enabling the calculation of key parameters such as average or local Nusselt numbers. Conversely, numerical studies offer detailed insights and visualisation of difficult-to-measure quantities. The relative advantages and limitations of these approaches remain a critical consideration when selecting an appropriate research method. Thus, this study aims to provide a comprehensive comparison between the experimental and numerical approaches to guide researchers in choosing the most suitable one for their objectives.

2. EXPERIMENTAL SETUP AND COMPUTATIONAL MODELLING

2.1. Experimental setup

Coetzee et al. [2] was the first study to extensively investigate local laminar Nusselt numbers for horizontal circular tubes with a UWT boundary condition, and a brief overview of the experimental setup is provided here for completeness. The experimental setup, shown in Fig. 1, consisted of two flow loops: one circulated water through a 5-m-long copper test section with an internal diameter of 4.9 mm and outer diameter of 6.5 mm, while the other circulated water through a water bath containing five 1-m-long sections, providing a uniform temperature environment around the copper tube. The novel testing procedure and water bath design enabled the measurement of mean fluid temperature at the end of each water bath section, allowing the calculation of local Nusselt numbers. Initially, only the first meter of the test section was exposed to external flow from water bath section one, while subsequent water bath sections remained empty, and the remainder of the tube length insulated. Water bath sections were then incrementally activated by removing insulation and introducing flow, progressively exposing all five metres of the tube to external water bath flow. The test section outlet temperature was measured in each instance and taken as the mean fluid temperature at the end of the last active water bath section. A mixer was placed at the inlet of each water bath section to improve wall temperature uniformity, and the six outer walls of each water bath section were insulated to minimise environmental heat losses or gains. A flow-calming section established a square-edge inlet configuration to achieve hydrodynamically and thermally developing flow. T-type thermocouple probes measured inlet and outlet temperatures, while wall temperatures were recorded at 26 stations along the test section using three T-type thermocouples at each station. Fluid temperatures within each water bath section were measured using T-type thermocouples positioned near the inlet and outlet of each water bath section.

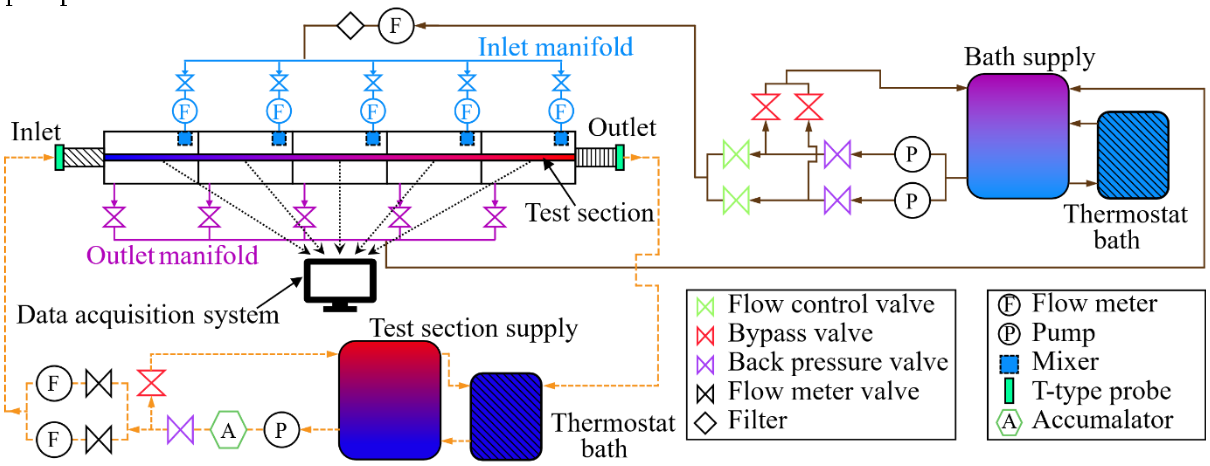

Fig. 1: Schematic of the experimental setup showing two flow loops. The first (dotted orange lines) facilitated flow through the copper tube test section, while the second (solid brown lines) circulated flow through five water bath sections. Adapted from [2].

2.2. Computational domains

Steyn et al. [6] effectively leveraged the advantages of numerical investigations by investigating several parameters that are difficult to measure experimentally and a brief overview of the computational domains is provided here for completeness.

2.2.1. Model 1: Replica of experimental setup

Model 1 replicated the experimental setup of Coetzee et al. [2] using two computational domains: one for water bath section one and another for sections two to five. The first domain shown in Fig. 2(a) included a segment of the flow calming section (pink region), forming the internal fluid region along with the flow through the copper tube. The second fluid region represented the water bath flow (green region). Of the eight polycarbonate water bath walls, only two were modelled—a solid wall (orange region) at the start of the water bath section and a shell conduction wall at the end—while the remaining six were treated as adiabatic to reflect insulation present during the experiments. The internal fluid region's inlet and outlet are indicated as velocity inlet 1 and pressure outlet 1, respectively, in Fig. 2(a). A uniform velocity and temperature profile was imposed at velocity inlet 1, as the preceding flow calming section was insulated and straightened the flow. Velocity inlet 2 represented the water bath section inlet, where the mixer was modelled, while pressure outlet 2 corresponded to the section outlet. The temperature at velocity inlet 2 and the boundary condition of the shell conduction wall matched the experimentally measured water bath temperature near the section inlet. The second computational domain, shown in Fig. 2(b), modelled water bath sections two to five. The boundary conditions were updated at four locations: velocity and temperature profiles at the end of the previous section were applied at velocity inlet 1 of the subsequent section; temperature profiles at the tube wall and shell conduction wall at the end of the previous section were imposed as boundary conditions for the respective walls at the beginning of the next section; and the temperature at velocity inlet 2 was updated to match the experimentally measured water bath temperature.

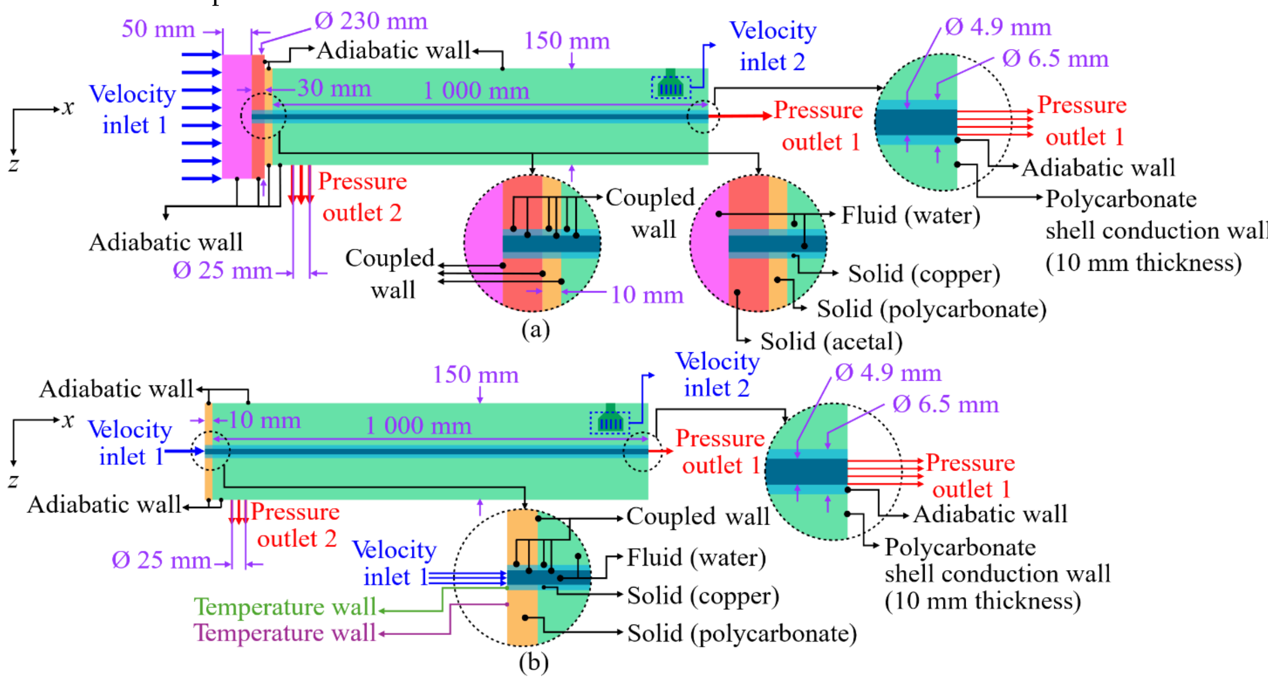

Fig. 2: Top view of (a) computational domain 1 and (b) computational domain 2 for Model 1. Adapted from [6].

2.2.2. Model 2: Ideal boundary condition

The computational domain for Model 2, shown in Fig. 3, applied uniform temperature and velocity profiles at the tube inlet, ensuring hydrodynamically and thermally developing flow, with an ideal UWT boundary condition applied at the outer tube wall.

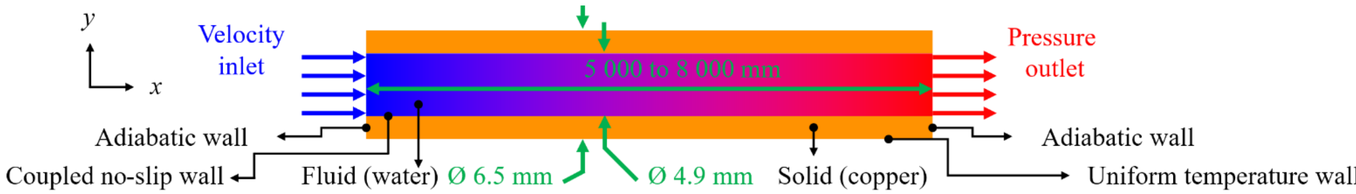

Fig. 3: Computational domain for Model 2. Adapted from [6].

2.3. Validation

Extensive experimental [2] and numerical [6] validations were conducted. The average experimental Nusselt numbers aligned well with mixed [3, 4] and forced convective correlations [12], with average deviations ranging from 3.8% to 9.4% [2]. The local experimental Nusselt numbers showed good agreement with forced convective correlations [9, 10, 12] near the inlet and divergence downstream due to increasing free convection effects.

The numerical local Nusselt numbers of Model 1 closely matched experimental data [2] with an average deviation of 6.9%. Although the local Nusselt number x/D = 10.2 was 26.7% larger than the experimental value, the numerical result was considered more accurate due to the use of the extracted inlet wall temperature in its calculation. In contrast, the experimental calculation assumed the inlet wall temperature to be equal to the first wall temperature measured at x/D = 10.2, an assumption that was less reliable due to wall temperature non-uniformities. Minor exceedances of Model 1 beyond average experimental uncertainty in water bath sections four and five were deemed acceptable, given the likely increase in local experimental uncertainty due to reduced wall-fluid temperature differences within these sections. Model 2's local Nusselt numbers deviated on average by 5.6% from the experimental data [2] up to x/D = 624.5. Beyond this point, the local Nusselt numbers declined toward the theoretical fully developed value of 3.66, while those of Model 1 and the experimental data fluctuated at approximately 5.5 due to enhanced external convection effects within the water bath sections.

3. RESULTS

3.1. Experimental approach

Fig. 4 shows the experimental local Nusselt numbers [2] (black triangular markers) at an inlet Reynolds number of 902 and an average wall temperature of 29.1°C. The experimental mixed convective UWT trend—an initial decline to a minimum, followed by a peak and a near-constant region—deviates notably from trends predicted by forced convective correlations, such as the Churchill and Ozoe [9] correlation (purple line in Fig. 4). Experimental average Nusselt numbers also revealed the onset of transitional flow at Reynolds numbers above 2 000 [2]. While the critical Reynolds number depends on several complex factors, experimental measurements simplify its identification by capturing flow behaviour directly. These results highlight a core advantage of experimental studies: the ability to capture complex phenomena—such as surface roughness effects, transitional flow, and mixed convective effects—through direct measurements of temperature and pressure drop which reflect the physical behaviour of the system without reliance on simplifying assumptions. As a result, experimental data remain physically meaningful and representative of real-world conditions. It is for this reason that empirical correlations are often the most reliable and robust method for predicting heat transfer and fluid flow behaviour in practical engineering applications and experimental data remain essential for validating numerical models, ensuring that computational predictions align with physical reality.

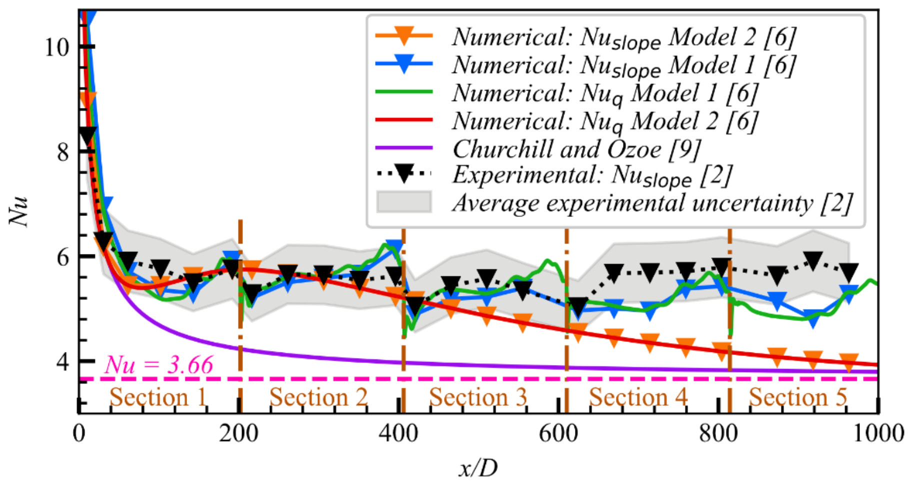

Fig. 4: Experimental [2] and numerical [6] local Nusselt numbers at an inlet Reynolds number of 902 and an average wall temperature of 29.1°C.

While experimental flow visualisation techniques such as Particle Image Velocimetry and Laser Doppler Anemometry exist, these are typically limited to specific regions of the flow field and are challenging to implement in UWT setups due to interference from the external heating method. Moreover, parameters such as boundary layer thicknesses, velocity and temperature profiles, and the strength of buoyancy-induced secondary flow vortices are extremely challenging to measure experimentally. The impact of these limitations is evident in the experimental evaluation of the strength of buoyancy-induced secondary flow using the local Grashof number [2], which provides valuable insights but does not isolate the strength of buoyancy-driven secondary flow. Similarly, thermal boundary layer development could not be analysed experimentally [2], leaving conclusions about the interaction between the thermal boundary layer, secondary flow effects, and their impact on the local Nusselt number to remain qualitative. Thus, while pressure and temperature measurements permit the calculation of friction factors and Nusselt numbers, UWT experiments remain limited by challenges in measuring and visualising key parameters. Consequently, conclusions regarding the underlying influences of observed experimental trends often rely on qualitative reasoning rather than being inferred based on quantitative analyses.

The near constant experimental local Nusselt number region observed downstream of the local peak (e.g., beyond x/D = 200 in Fig. 4) was attributed to sustained internal free convection effects [2]. However, numerical results revealed that this trend arose from enhanced external convection near the water bath inlets induced by the mixer [6]. This illustrates a limitation of experimental studies: while they can capture a broad range of phenomena, they can also capture effects unrelated to the aim of the study, which can lead to the misattribution of observed trends to the wrong physical influence.

To avoid mechanical strain, thermocouple lead wires are typically attached to the test section at approximately 20 mm from the thermocouple junction [13], limiting the proximity of wall temperature measurement stations. Moreover, measurement locations must be prepared before testing, even though regions requiring finer spatial resolution often only become apparent after results are analysed. As a result, trends that develop and dissipate between measuring locations may go undetected, posing challenges for experimental parametric investigations. For instance, experimental results showed local Nusselt number peaks at the same axial position for various Reynolds numbers at a fixed bath temperature [2]. However, numerical results revealed slight axial shifts of these peaks with Reynolds number [6], which could not be captured due to the measurement spacing in the experimental setup.

This limitation extended to mean fluid temperature measurements, which were measured at six axial locations using a non-intrusive method, with curve fitting used to estimate mean fluid temperatures at the wall temperature measurement locations [2]. In the absence of wall heat flux data, which is difficult to obtain under UWT conditions, local Nusselt numbers were calculated using a central differencing approximation for the slope of the mean fluid temperature. Fig. 4 compares the numerical local Nusselt numbers of Models 1 and 2 based on known local wall heat flux (Nu_q, solid lines) and slope-based estimates (Nu_{slope}, triangular markers). The two calculation methods correspond well, confirming the experimental approach's accuracy. However, the additional uncertainty introduced by the curve fit coefficients increased the uncertainty of the experimental local Nusselt numbers. Furthermore, measurement uncertainties impact experimental accuracy, particularly in regions with small pressure drops and temperature differences, limiting the ability to observe certain trends. At a Reynolds number of 600, experimental local Nusselt numbers fell well below the expected fully developed value of 3.66 [2]. However, numerical results indicated that where local Nusselt numbers fell below 3.7, the maximum wall-fluid temperature difference was 0.1°C. Since this corresponds to the accuracy of the thermocouples, it is likely that measurement uncertainties arising from such small wall-fluid temperature differences prevented experimental results from capturing the expected stabilisation of the local Nusselt number at 3.66.

Experimental investigations are resource-intensive, requiring significant financial and logistical investment for setup construction, calibration, and repeatability testing. While operational setups enable efficient variation of conditions such as Reynolds or Grashof numbers, physical modifications—such as altering tube geometry, working fluids, or inlet conditions—remain labour-intensive and costly. Consequently, experimental studies are generally better suited to focused investigations involving flow rate or heating intensity variations rather than geometric or system parameter variations.

3.2. Numerical approach

Validation of the numerical results required not only experimental results but also detailed knowledge of the setup, data reduction methods, and temperature measurements at key locations. For laminar UWT flow, validation against experimental results is essential, as analytical solutions typically assume constant fluid properties, limiting their applicability to real-world conditions. This dependence on experimental data and detailed experimental insight represents a fundamental limitation of numerical studies, as without successful validation, it cannot be confirmed that numerical results accurately capture physically realistic phenomena.

Models 1 and 2 assumed laminar flow within the tube and thus could not capture transitional behaviour numerically, therefore, simulations were limited to inlet Reynolds numbers below 2 000 [6]. Nevertheless, this reflects a key limitation of numerical studies: they can only model phenomena that align with their underlying assumptions. Unlike experimental studies, which inherently capture complex physical behaviour, numerical investigations may overlook such behaviour unless they are specifically incorporated into the modelling approach. Therefore, while assumptions are necessary to maintain computational feasibility, they must be carefully selected based on experimental data to avoid compromising the accuracy and validity of numerical results.

Fig. 5 shows the local Nusselt numbers (red), circulation strength (green), and thermal boundary layer thicknesses (blue) of Model 2 at inlet Reynolds numbers of 1 000 (solid lines) and 2 000 (dashed lines) at an initial wall-fluid temperature difference of 30°C. It highlights a key advantage of numerical studies: the ability to extract any parameter at any location in the flow domain. This enables the independent analysis of circulation strength and thermal boundary layer thicknesses prior to evaluating their combined influence on the local Nusselt number and provides quantitative evidence for the observed local Nusselt number trends. Furthermore, this advantage allows numerical results to identify that higher external heat transfer coefficients within the water bath caused the constant experimental local Nusselt number region, rather than sustained internal free convection effects. These findings demonstrate how numerical investigations facilitate the independent analysis of multiple parameters, which is essential for understanding the causes of trends in parameters reflecting the combined influence of several factors, such as Nusselt numbers and friction factors. Moreover, the visualisation of temperature contours and velocity streamlines provide an explanation of the physical phenomena behind observed trends in the thermal boundary layer [6]. This demonstrates how the ability to extract and visualise any parameter enhances the depth of understanding of the flow and heat transfer characteristics attainable through numerical investigations.

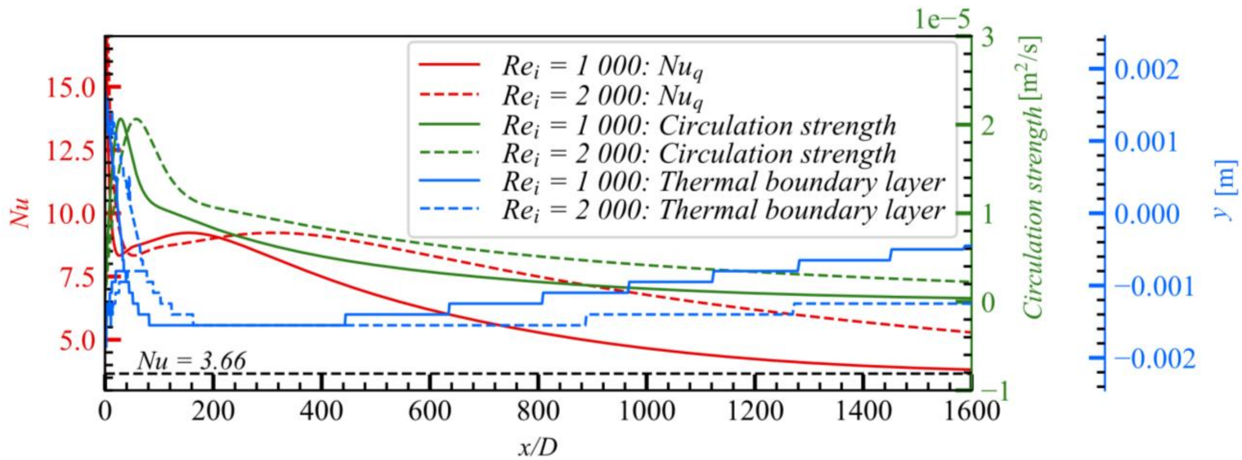

Fig. 5: Numerical local Nusselt numbers (red), circulation strength (green), and thermal boundary layer thicknesses (blue) of Model 2 for an inlet Reynolds number of 1 000 (solid lines) and 2 000 (dashed lines) at an initial wall-fluid temperature difference of 30°C. Adapted from [6].

Fig. 5 shows that, at a fixed initial wall-fluid temperature difference, changes in Reynolds number affected the axial locations of the local Nusselt number peak and trough but not their magnitudes [6]. These trends were observable due to the high spatial resolution and absence of measurement uncertainty in the numerical data. In contrast, experimental results could not capture shifts in extrema positions due to limited measurement density, while variations in extrema magnitudes likely arose from both this limitation and measurement uncertainty. This showcases how the high data density and lack of measurement uncertainties in numerical results enable precise parametric studies, even in regions of small temperature differences or pressure drops, as evidenced in Fig. 5 where the local Nusselt numbers asymptotically approached 3.66.

Although the initial investment in computational hardware and setup may be substantial, numerical models offer superior cost- and time-efficiency for parametric studies involving geometric or system modifications—such as changes in tube dimensions, working fluid, or inlet conditions—since these can be implemented without additional costs and with minimal additional time requirements. In contrast, experimental investigations require significant additional time and financial resources to implement such changes. Both approaches, however, accommodate variations in operating conditions, such as flow rate or wall-fluid temperature differences, with relative ease. The time requirements of numerical investigations are highly dependent on the computational resources available, making direct comparisons to experimental timelines context specific. However, for complex phenomena—such as transitional flow, turbulent flow, or surface roughness effects—numerical time-efficiency may diminish, as the need for high-fidelity models like Large Eddy Simulation increase computational demands, potentially surpassing experimental time and resource requirements.

3.3. Integrated experimental and numerical approach

An integrated experimental and numerical approach leverages the strengths of both methods while mitigating their limitations. Access to detailed experimental data, setup information, and data reduction methods in an integrated approach prevents the dependence of numerical investigations on these details from becoming a limiting factor. This enhances the ability to successfully validate numerical results, ensuring they reflect physically realistic behaviour. Due to the availability of detailed experimental information in an integrated approach, accurate numerical replicas such as Model 1 can be developed. Fig. 6 shows the velocity streamlines and temperature contours of Models 1 and 2 alongside the numerical and experimental local Nusselt numbers, with Model 1 visualisations reflecting the expected velocity streamlines and temperature contours present during experimental testing. This illustrates how the ability of numerical investigations to extract and visualise any parameter can mitigate the inability of experimental investigations to do the same. An integrated approach thus enables deeper insight into the underlying mechanisms driving experimental and numerical results by retaining the numerical ability to isolate and quantitatively assess individual parameters, thereby reducing the risk of misattributing observed trends to the wrong physical influence. A combined approach thus supports qualitative interpretation with quantitative evidence while ensuring physically meaningful numerical results.

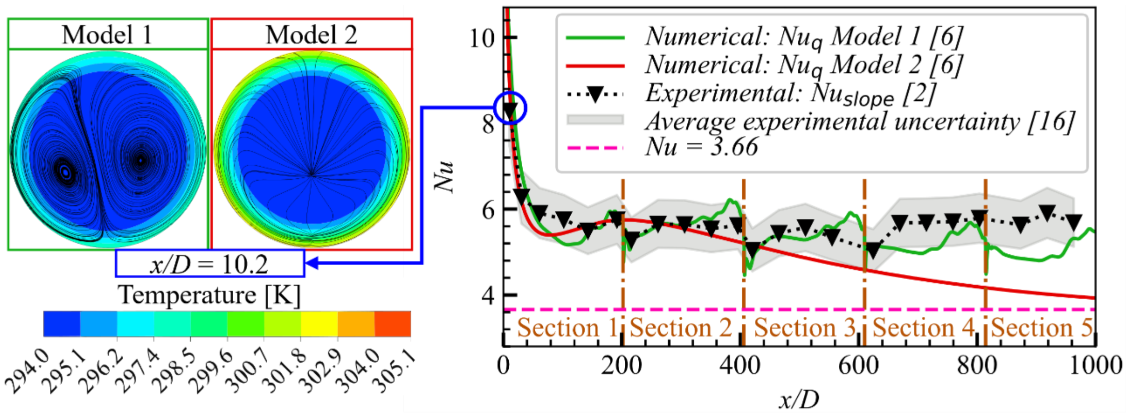

Fig. 6: Experimental [2] and numerical [6] local Nusselt numbers with temperature contours and velocity streamlines at *x/D* = 10.2 for Models 1 (green outlines) and 2 (red outlines) at an inlet Reynolds number of 902 and an average wall temperature of 29.1°C.

By combining experimental and numerical results, an integrated approach enables detailed assessment of the deviations between experimental and idealised conditions, such as inlet profiles and wall temperature uniformities. This is exemplified in Fig. 6, where velocity streamlines at *x/D* = 10.2 reveal non-symmetrical vortices in Model 1, attributed to fluid rotation caused by the interface between the flow-calming section and the tube entrance, whereas streamlines of Model 2 exhibit radial flow toward the tube centreline, indicating the dominance of shear-stress-driven secondary flow [6]. Such comparisons enable quantification of the impact of non-ideal experimental conditions, which is particularly valuable in heat exchanger design, where understanding deviations from idealised assumptions is critical.

An integrated approach enables strategic resource allocation by only conducting experiments at critical points, such as at parameter extremes or when capturing complex phenomena, while using numerical simulations to populate the broader parameter space with dense data free of measurement uncertainties. This ensures that fundamental physics are accurately captured while enabling broad and high-accuracy parametric investigations to be conducted quickly and at minimal cost. In regions with high experimental uncertainty, numerical results also provide reliable supplementary data. Moreover, numerical results can validate experimental data reduction by comparing methods using approximations with those using directly extracted numerical values, as was done in Fig. 4.

Empirical correlations can also benefit from numerical augmentation. While key experiments establish physically realistic baselines, numerical results can refine their accuracy by capturing detailed parametric variations that experiments alone may not resolve. Numerical models can also confirm the consistency of empirical correlations that use dimensionless analysis by testing their accuracy across different parameters, such as different fluid types and tube dimensions. Additionally, experimental observations of complex phenomena inform numerical model development by highlighting the need for refinements to capture such phenomena or by identifying parameter ranges where numerical assumptions remain valid.

By combining numerical and experimental approaches, researchers retain the advantages of each method while mitigating their limitations. This synergy yields physically realistic, reliable, and accurate results, broadens parametric investigations, refines empirical correlations, and deepens the understanding of complex flow and heat transfer behaviours while reducing costs and improving time efficiency.

4. CONCLUSIONS

This study presented a comparative evaluation of the advantages and limitations of experimental and numerical approaches in investigating laminar UWT internal flow, providing a basis to guide researchers in selecting the most suitable approach for their objectives. It was found that experimental investigations offer direct measurements that reliably capture complex flow behaviour and ensure physically realistic results. Nevertheless, they are constrained by spatial resolution limits, measurement uncertainties, and the inability to directly quantify and visualise certain parameters. Moreover, the substantial time and resource demands associated with modifying experimental setups or working fluids render them less suitable for extensive parametric investigations. Despite these challenges, experimental methods remain indispensable for empirical correlation development and provide essential validation data for numerical investigations. In contrast, numerical studies allow for the extraction and visualisation of all parameters at any location within the flow domain, enabling a more comprehensive and quantitative analysis of the underlying mechanisms driving flow and heat transfer behaviour. Numerical studies are also ideal for parametric investigations due to the absence of measurement uncertainties, high spatial resolution of results and the minimal additional time and cost requirements associated with changing geometric and system parameters. However, numerical investigations depend heavily on experimental data for validation and can only capture behaviour consistent with their assumptions.

An integrated experimental and numerical approach enables efficient resource allocation by reserving experimental efforts for targeted cases where ensuring physically realistic results are essential such as parameter extremes or cases involving substantial physical complexity, while using numerical models to populate the broader parameter space with high-resolution data that do not contain measurement uncertainties. This combined strategy offsets individual limitations while leveraging complementary strengths: experimental data supports accurate numerical model development and validation, while numerical simulations provide detailed insights through visualisations and the calculation of difficult-to-measure parameters. Together, they can deliver physically realistic results, deepen fundamental understanding, and refine empirical correlations with optimal use of time and financial resources. Therefore, an integrated approach is recommended where feasible.

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