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A Review of Boundary Layer and Turbulence Theory and Their Impacts on Heat Exchanger Performance

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Abstract. Growing thermal loads in modern high-density electronics, data-center equipment and electrified vehicles have significantly increased the relevance of compact heat exchangers and liquid cooling channels for system efficiency. In forced convection, the dominant contribution to thermal resistance comes from the thermal boundary layer near the surface, therefore, the nature of the flow in this layer (laminar, transitional or turbulent) significantly affects heat transfer and hydraulic resistance. The goal of this review is to analyze the formation of boundary layers, the transition to turbulence, and the coupled thermal and hydraulic effects of turbulence based on literature review, theoretical synthesis and comparative analysis, with a focus on heat transfer enhancement and hydraulic resistance induced by the same boundary layer disturbances. The key issue is how the enhancement of heat transfer and the increase in hydraulic resistance, stemming from the same boundary layer disturbances, should be evaluated and optimized. The concepts of the j/f ratio, performance evaluation criteria (PEC), field synergy and entropy generation minimization will be compared, and passive and active enhancement techniques are classified according to their disturbance and regeneration of the boundary layer.

Keywords: boundary layer, turbulence, convective heat transfer enhancement, flow resistance, performance evaluation criteria

1. Introduction

Thermal management has become a key constraint in the design of small-scale energy systems and electronic devices. Experiments on the hybrid mini-channel/jet cooling approach have shown that contemporary designs must reject high heat fluxes while keeping pressure drop and thermal resistance low [1]. On the fundamental physical level, the problem is largely controlled by the near-wall region. The fluid viscosity and no-slip conditions cause the velocity boundary layer to form, whereas the temperature difference between the wall and the fluid results in the formation of the thermal boundary layer [2, 3]. Since the sharpest gradients of velocity and temperature develop in the near-wall region, the variations in the boundary-layer development lead to changes in the wall heat flux and wall shear.

The present paper, however, reviews boundary layer and turbulence theories in the context of thermal hydraulics and addresses one key question: when the same disturbance enhances near-wall

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mixing, while increasing friction at the same time, how should the combined optimization of heat transfer enhancement and friction be performed? The review is organized as follows. Section 2 explains the basic concepts of velocity and thermal boundary layers, the influence of the Prandtl number, and the problem of laminar-to-turbulent transition. Section 3 analyzes the enhancement-resistance interaction using the Nusselt number, the friction factor, j/f-type characteristics and PEC. Section 4 compares passive and active techniques and highlights the limitations of existing correlations and turbulence modelling. Literature review, theoretical synthesis and comparative analysis are applied throughout.

2. Fundamentals of the boundary layers and turbulence

2.1. Formation of velocity and thermal boundary layers

When fluid flows over a solid surface, a sharp velocity gradient develops near the wall because of viscosity and the no-slip condition. When a temperature difference exists between the surface and the fluid, a thermal boundary layer develops near the wall [2, 3]. The ratio of their thicknesses depends partially on the Prandtl number, $Pr = \nu/\alpha$. Fluids with a low Pr value diffuse heat quickly, while water and water-glycol mixtures have a high momentum to thermal diffusivity ratio. Therefore, the same surface perturbation can cause different thermal effects in different working fluids.

2.2. Laminar, transitional and turbulent flow: reynolds number and transition

Reynolds number, $Re = \rho VD / \mu$, measures the ratio between inertia and viscosity, but transition is a process and rather than a critical phenomenon. External flows and internal flows have their respective characteristic lengths, while the compact channels incorporate curvature and roughness and repeated separation. For smooth internal flows, transition starts around Re = 2300, but for practical heat exchanger channels, transition is sensitive for thousands of Reynolds numbers. This has been shown for chevron channels, where 3D sub-streams and vortices generate turbulence-like mixing at relatively low Re values [4].

2.3. Convective heat transfer from a boundary-layer perspective

In forced convection, the maximum value of temperature difference normally occurs near the wall, thus making the performance of convective flow characterized by Nu=hD/k. Thin and repeated boundary layer regeneration results in increased temperature difference and h. Corrugation, surface roughness, and local recirculation can all promote this mechanism, however, they also cause increased resistance. Experiments investigating chevron angle and surface roughness have shown increases in both the heat transfer coefficient and pressure drop [5]. The underlying concept for design is therefore boundary layer regeneration control.

3. The dual effect: coupled heat-transfer enhancement and flow resistance

3.1. Heat-transfer side: turbulent enhancement and engineering correlations

Turbulent fluctuations transfer momentum and energy throughout the mean flow, whereas separation, reattachment and secondary flows regenerate the fluid adjacent to the walls. Engineering relationships that relate Re, Pr and Nu can still be applied, and the Colburn factor j provides a

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convenient heat transfer relationship. Correlations of friction and Colburn factor for chevron plate heat exchangers have been created by Lee and Lee and have been used for shape optimization [6]. This illustrates the importance of doing such in both heat transfer and hydraulics in three dimensional channels.

3.2. Resistance side: friction factor, pressure drop and pumping power

The very same mechanisms that increase Nu also increase momentum losses. The friction effect is dependent on Re, roughness, and shape of geometry, while the separation and recirculation effects cause form drag. Due to the square dependency of pressure losses on velocity, pumping power can increase significantly as the flow rate increases. The experiments with rough chevron-plates clearly show the tradeoff – enhanced performance is accompanied by an increase in pressure drop [5].

3.3. Unified performance evaluation: from single indicators to thermal-hydraulic coordination

Four evaluation frameworks are compared in this section. The j/f-type evaluation considers the thermal transport relative to friction, and is appropriate for compact exchangers [6]. The PEC methodology compares the enhancement in Nusselt number with the corresponding increase in friction relative to a baseline configuration, it has been used to optimize dimpled surfaces [7]. The field synergy approach evaluates enhancement based on the interaction between the velocity and the temperature gradient, while more recently this logic has been expanded to systems with temperature-dependent properties [8]. On the other hand, entropy generation is a methodology that evaluates the irreversibilities associated with both heat transfer and flow friction, which may be linked to economical considerations [9]. These approaches do not define the same optimum: j/f and PEC are dependent on the reference criteria, field synergy is mostly mechanical, and entropy generation depends on the system boundaries.

4. Enhancement techniques, current limitations and future directions

4.1. Classification of heat-transfer enhancement techniques

Passive methods have roughness features, pin fins, interrupted fins, microchannels, dimples, wire mesh, and vortex generators. Although they vary in shape, they share a common boundary-layer mechanism: delaying boundary-layer growth, inducing secondary flows, or regenerating the boundary layer. Optimum micro surface roughness in plate heat exchangers has resulted in favorable PEC compared to just increasing roughness [10]. The active techniques introduce external excitation where pulsation can affect heat transfer through micro channels and magnetic field can disturb magnetic fluid boundary layers [11, 12].

4.2. Current limitations of theory, correlations and experiments

Transferability is another issue. Classical correlations rely on well-developed passages, while compact exchangers have repeated redevelopment, low Reynolds number transitions and three-dimensional flow. The problem of CFD simulation includes model dependency. Laminar and two-equation models in plate exchangers give different results for thermal-hydraulic calculations [13]. Transition-SST gave better prediction results than k-ε models in mini-channel and jet heat sink [1]. All these facts point out the problem of turbulence modeling impact on Nu prediction. However, the

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experiments are still required. Local measurements in microchannels are not easy and expensive to be conducted.

4.3. Development directions and optimization strategies

Future research should move away from empirical tuning of a single variable toward multi-objective, physics-based optimization. CFD can be used to validate the existence of vortexes, separation and wall gradients, and response surfaces can be used to decrease the computational costs involved in design searches. In dimple design optimization, there has been successful integration of CFD and response surface method optimization [7], where airfoil corrugation was used to lower the pressure drop but keep a high heat transfer rate [14]. Recent work has successfully optimized Nu and PEC together for micro-surfaces [10].

5. Conclusion

This review has examined boundary-layer and turbulence theories in the context of thermal hydraulics and highlighted a key question: how can turbulence be used to enhance heat transfer without allowing the associated flow-resistance penalty to become excessive? Three conclusions can be drawn. First of all, the near-wall boundary layer is the key physical location controlling the convective thermal resistance and wall shear. The nature of flow – laminar, transitional, or turbulent – determines the rates at which momentum and heat are transferred between the wall and the core. Secondly, various enhancement techniques that appear to be different operate on the same principle. In other words, their benefits cannot be evaluated based on only the heat transfer coefficient or Nusselt number. Thirdly, the evaluation approach itself affects the definition of optimal performance. The j/f ratio and PEC make comparison possible from the thermal-hydraulic aspect, field synergy describes how the two fields work together, and entropy generation minimum deals with irreversibility. In summary, an efficient heat exchanger must induce turbulence in an area where turbulence can be beneficial.

The current review has three limitations. First, it is restricted mainly to single-phase forced convection and does not cover boiling and condensation, second, it is a qualitative review rather than a quantitative, normalized meta-analysis, and third, it cannot eliminate uncertainties associated with geometry-dependent correlations and turbulence-model selection. Future work should therefore be centered on robust correlations of the transition region, data across geometries, experimentally verified CFD results, and surrogate/machine learning approaches along with multi-objective optimization. An integration of PEC, entropy generation, and manufacturability as well as life cycle pumping energy would thus give a more practical approach to compact heat exchanger design.

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