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MODELING HEAT TRANSFER IN MULTIPHASE AND MULTIGEOMETRIC FLOWS OF NEWTONIAN FLUIDS IN PIPES AND CHANNELS

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Abstract: This study investigates the modeling of heat transfer in multiphase and multigeometric flows of Newtonian fluids within pipes and channels of various configurations. The research focuses on the development and analysis of mathematical and numerical models that describe the coupled processes of fluid flow and heat transport under different hydrodynamic and thermal conditions. Particular attention is given to the influence of flow geometry, phase interactions, and thermophysical properties on temperature distribution and heat transfer efficiency. The governing equations, including the continuity, momentum, and energy conservation equations, are formulated based on the principles of fluid mechanics and heat transfer. Numerical simulations are performed using advanced computational techniques to evaluate the effects of channel shape, flow regime, Reynolds number, and phase distribution on thermal performance. The results demonstrate that geometric complexity and multiphase interactions significantly affect local and average heat transfer characteristics. The proposed modeling approach provides valuable insights into the optimization of thermal systems employed in chemical processing, energy engineering, microfluidics, and industrial heat exchangers. The findings contribute to a deeper understanding of transport phenomena in complex flow environments and support the design of more efficient heat transfer equipment.

Keywords: heat transfer modeling, multiphase flow, Newtonian fluids, pipes and channels, computational fluid dynamics (CFD), energy equation, thermal transport, multigeometric flow systems, numerical simulation, convective heat transfer, finite element method, thermal optimization.

Introduction

Heat transfer in fluid flows through pipes and channels is a fundamental topic in fluid mechanics and thermal engineering, with widespread applications in energy systems, chemical processing, petroleum engineering, microfluidic devices, and heat exchanger technologies. The efficiency of many industrial and engineering systems depends on the accurate prediction of temperature fields and heat transfer rates under various flow and geometric conditions. As modern thermal systems become increasingly complex, the need for advanced mathematical models capable of describing coupled fluid flow and heat transfer processes has grown significantly.

Newtonian fluids, characterized by a linear relationship between shear stress and strain rate, are commonly encountered in industrial applications. Examples include water, air, light oils, and many engineering liquids. The thermal behavior of such fluids flowing through conduits is influenced by numerous factors, including flow velocity, fluid properties, boundary conditions, and channel geometry. In practical systems, flow domains often involve complex geometries and multiple interacting phases, which substantially affect transport phenomena and thermal performance.

Multiphase flows, involving combinations of liquid, gas, or solid phases, are particularly important in engineering processes such as boiling, condensation, slurry transport, oil and gas production, and cooling technologies. The interaction between phases introduces additional complexities due to momentum, mass, and energy exchange mechanisms. These interactions can significantly alter local temperature distributions, turbulence characteristics, and overall heat transfer

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efficiency. Consequently, the development of reliable models for multiphase heat transfer remains an active area of scientific research.

In addition to phase interactions, geometric variations in pipes and channels play a crucial role in determining flow structures and thermal characteristics. Straight, curved, converging-diverging, and non-uniform channels generate different velocity and temperature profiles, leading to variations in convective heat transfer rates. The optimization of channel geometry has therefore become an important strategy for enhancing thermal performance while minimizing energy consumption and pressure losses.

Recent advances in computational fluid dynamics (CFD) and numerical methods have enabled detailed investigations of complex heat transfer processes in multiphase and multigeometric flow systems. Mathematical models based on the conservation laws of mass, momentum, and energy can now be solved with high accuracy using finite element, finite volume, and finite difference techniques. These approaches provide valuable insights into the mechanisms governing thermal transport and allow engineers to predict system behavior under a wide range of operating conditions.

The objective of this study is to develop and analyze mathematical models for heat transfer in multiphase and multigeometric flows of Newtonian fluids in pipes and channels. The research aims to investigate the influence of geometric configurations, flow parameters, and phase interactions on thermal performance through numerical simulations. The results are expected to contribute to the improvement of thermal system design and the optimization of engineering applications involving complex fluid flow and heat transfer processes.

Mathematical Formulation of the Problem

The modeling of heat transfer in multiphase and multigeometric flows of Newtonian fluids is based on the fundamental conservation laws of mass, momentum, and energy. Consider an incompressible Newtonian fluid flowing through pipes and channels of different geometric configurations. The flow field and temperature distribution are governed by the following equations.

Mathematical Formulation

Heat transfer in Newtonian fluid flow through pipes and channels is described by the conservation laws of mass, momentum, and energy. Assuming incompressible flow, the governing equations are

$$\nabla \cdot u=0,$$

where u=(u,v,w) is the velocity vector.

$$\rho \cdot c_p \quad (\partial t/\partial T \quad +u \cdot \nabla T)=k\nabla^2 T+Q.$$

These equations describe the velocity and temperature fields within the computational domain and serve as the basis for numerical simulations.

Multiphase Flow Modeling

Multiphase flow consists of two or more interacting phases, such as liquid–gas or liquid–solid systems. In this study, the interaction between phases is represented using volume fractions and interfacial heat exchange. The conservation of phase volume satisfies

$$\sum_{i=1}^{n} \alpha_i =1$$

Interphase heat transfer significantly influences the temperature distribution and overall thermal performance of the system.

Effect of Channel Geometry

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The geometry of pipes and channels strongly affects both hydrodynamic and thermal characteristics. Straight channels provide reference conditions, whereas curved and converging-diverging channels generate secondary flow structures that enhance fluid mixing. Corrugated channels improve convective heat transfer by increasing turbulence, although they also produce larger pressure losses. Therefore, channel geometry plays a critical role in optimizing thermal efficiency.

Numerical Method

The governing equations were solved using the Finite Element Method (FEM). The computational procedure included geometry generation, mesh discretization, application of boundary conditions, numerical solution of the governing equations, and post-processing of temperature and velocity fields. Grid independence tests were performed to ensure the accuracy and stability of the numerical results.

Results and Discussion

Numerical simulations indicate that both multiphase interactions and geometric complexity significantly influence heat transfer characteristics.

The results reveal that:

Increasing Reynolds number enhances convective heat transfer.

Curved and corrugated channels produce higher Nusselt numbers compared to straight channels.

Multiphase systems exhibit improved thermal performance due to increased interfacial area and mixing effects.

Heat transfer enhancement is accompanied by increased pressure drop, requiring optimization between thermal efficiency and pumping power.

Temperature contour distributions demonstrate more uniform thermal fields in geometries that promote secondary flow formation and phase interaction. The analysis confirms that the combined effects of channel geometry and multiphase dynamics play a crucial role in determining overall thermal performance.

Thus, the developed mathematical and numerical framework provides an effective tool for investigating heat transfer in complex Newtonian multiphase flow systems and can be applied to the design and optimization of industrial thermal equipment.

Conclusion

This study presented a comprehensive mathematical and numerical investigation of heat transfer in multiphase and multigeometric flows of Newtonian fluids within pipes and channels. The governing equations for mass, momentum, and energy conservation were formulated to describe the coupled hydrodynamic and thermal transport phenomena. The developed model incorporates the effects of fluid properties, channel geometry, and phase interactions, providing a reliable framework for analyzing complex thermal flow systems.

The numerical analysis demonstrated that both the flow regime and geometric configuration have a significant influence on heat transfer performance. Higher Reynolds numbers lead to enhanced convective heat transfer due to improved fluid mixing, while curved, converging-diverging, and corrugated channels generate secondary flow structures that increase thermal transport efficiency. Furthermore, multiphase flow systems exhibit superior heat transfer characteristics compared with single-phase flows because of the additional interfacial heat exchange and increased mixing between phases.

The results also indicate that improvements in heat transfer are generally accompanied by higher pressure losses, emphasizing the importance of balancing thermal efficiency and hydraulic performance during system design. Therefore, the optimization of channel geometry and operating conditions is essential for achieving energy-efficient thermal systems.

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Overall, the proposed mathematical model and numerical methodology provide an effective approach for predicting heat transfer in complex Newtonian fluid flows. The findings can be applied to the design and optimization of heat exchangers, cooling systems, chemical reactors, energy conversion devices, and microfluidic technologies. Future research may extend the present work by incorporating non-Newtonian fluids, turbulent multiphase flows, phase-change phenomena, and three-dimensional transient simulations to improve the accuracy and applicability of heat transfer models in advanced engineering systems.

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