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Editorial

Recent Advances in Fluid Mechanics and Transport Phenomena

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Transport phenomena draw from the fields of continuum mechanics and thermodynamics with diverse industrial applications. A commonality among these applications with fluids is their reliance on the constitutive equations of mass, momentum, and energy conservation laws, which are employed pervasively in engineering disciplines involving energy conversion, heat engine, heat/mass transfer, and fluid machinery. Recently, the performance improvement of heat engines, energy saving strategies, convective cooling to cope with the intensified power density of eclectic devices or systems, and energy harvesting are progressively connected with the global goal of reducing greenhouse gas emissions. The prospective advancements in these regards are closely associated with the transport phenomena with single- and multiphase flows. Considering the significance of multiphase flows for developing a clean, low-carbon, and efficient energy system, Zhu et al. [1] summarized a wide range of transport phenomena with multiphase flows for various energy applications. Due to the coexistence of multiple phases, states, and components, as well as the intricate interactions among them, the comprehension and, hence, the harness of multiphase flows to advance their applications in the engine and energy sectors require the coherent cooperation between academia and industries. While the emerging rifeness of electric vehicles is expected under the incentive of zero carbon emission, aero transportation still relies heavily on gas turbine engines. The explorations of the transport phenomena in gas turbine engines are under constant pursuit to improve their performance and engine saving. In [2], NASA's role and contributions to gas turbine engine development were reviewed. The technical advancements in the designs of compressors, combustors, and turbines, within which complex fluid mechanics with and without heat transfer occur, were investigated for increasing engine efficiency and power density. Above all, the subject of fluid mechanics and transport phenomena is deeply integrated with future developments in energy, engine, and power conversion. The main articles that summarize recent technological developments in this respect are presented here.

Energy saving for fluid machinery and heat engines is mainly achieved by improving their energy conversion efficiency. For heat exchangers, the thermal performance index that accounts for the augmentations of heat transfer rate and flow resistance is adopted to assess the energy saving effectiveness. For gas turbine engines, recent studies for improving their fuel economy have probed deeply into the transport phenomena with burning sustainable fuel [3] and under engine-representative conditions [4,5]. The flame stability of combustion in swirling flows is generally improved due to the formation of toroidal recirculation zones that reduce combustion lengths by promoting the entrainment of ambient fluid and fluid mixing, which have been commonly adopted for a high-intensity combustion process. The attempt to reduce carbon emission has led a recent study on hydrogen flames. Kang et al. [3] conducted large eddy simulations to examine the dynamic response of lean-premixed pure hydrogen-air flames to upstream fluctuating velocities to understand the spatially concentrated heat release dynamics. As an increase in thrust-to-weight ratio and a lower noise emission in a gas turbine engine often elevate blade loading and raise the risk of stall, Sun et al. [4] aimed to improve the stability of an axial compressor with noise reduction by way of metal casing treatment. The mechanism for enhancing the compressor's stability

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by installing foam metal was addressed by analyzing the near-casing pressure distribution and stall process. Wang et al. [5] considered the non-uniform temperature and thermal radiation at the exit of a combustor that imposed adverse thermal impact on its adjacent turbine blade. They proposed an integrated numerical simulation for a combustor-guide vane–rotating blade combined structure running under engine-representative conditions. The temperature distributions of the turbine inlet were correlative to the swirling flame, the dilution hole injection flow, and the cooling airflow through the combustor liner. At the exit of the combustor, the localized secondary flow promoted the mixing of hot streaks and cold fluid, leading to the moderation of temperature unevenness for the rotor blades.

The attempt to increase thermodynamic efficiency of a gas turbine engine by increasing its turbine entry temperature adds thermal load on the static and rotating blades. To ensure the structural integrity and life span of a gas turbine blade, complex internal cooling passages with various types of heat transfer enhancement methods were deployed in the leading, mid-chord, and trailing portions of a gas turbine blade. Chang et al. [6] reviewed current studies on heat transfer in rotating channels with various types of heat transfer enhancements. Under the effects of strong and buoyancy forces, together with the attempt to promote the aerothermal performances of the rotating coolant passages, the direct mixing of cold and hot flow streams was suggested. The thermal protection in a gas turbine engine can be enhanced by combining advanced materials with a double-wall effusion system to offer high internal or external cooling effectiveness. Gu et al. [7] explored the effects of material thermal properties and hole arrangement on the cooling performance of an impingement-pin-fin-effusion-based double-wall effusion system. The backward film injection scheme exhibited considerable improvements in overall cooling effectiveness.

The vicious circle of global warming resulting in weather extreme increases the energy consumption of heat pump and refrigeration systems. Under the energy-saving incentive, the development of efficient heat exchangers with single- and liquid–vapor two-phase flows is crucial for heat pumps or refrigeration systems. A mini/micro-channel heat exchanger offers a high heat transfer rate with compact structure, but the two-phase flow in a mini/micro channel is prone to mal-distribution due to phase separation. Xiong et al. [8] reported the development of two-phase flow distribution in mini/micro-channel heat exchangers. After summarizing the effects of geometry, operating conditions, and fluid properties on the two-phase flow distribution in evaporators/condensers, they presented current insert technologies and atomization devices for improving the uniformity of two-phase flow distribution in evaporators. For single-phase flows, Mousavi Ajarostaghi et al. [9] reviewed recent passive heat transfer enhancement methods, including insert technologies using twisted tapes, conical strips, baffles, winglets, coil/helical/spiral tubes, and extended or roughened surfaces, as well as the use of porous materials and nanofluids.

Green energy harvesting from aero- and hydro-power sources has prompted a large number of studies probing into the transport phenomena of associated fluid machineries. Ojo et al. [10] reviewed recent developments in floating offshore wind turbines for exploiting the vast wind resources available in deep waters, which requires integrating multidisciplinary technologies and understanding the dynamics of marine environment for design analysis and optimization. In this regard, the substructures of floating offshore wind turbines, their geometric shape parameterization, and the analysis methods used were summarized. Vertical-axis wind turbines appear to be the most common land-based wind energy harvesting devices. Ghasemian et al. [11] reviewed existing CFD studies on Darrieus vertical-axis wind turbines and proposed suggestions for the key aspects in numerical treatments. The operating and geometrical parameters that influence the optimization of the blade profile, performance improvements of guide vanes, wake interactions, noise reduction, stall control, and the effects of unsteady and skewed wind conditions were examined in detail. To harvest tidal current energy, Zhao et al. [12] conducted a numerical investigation to analyze the interactions between semi-active tandem flapping foils. Owing to the high-pressure region near the leading edge of the aft foil, the energy extraction performance was reduced compared to that of the single foil when the tandem distance was less than five blades. The aft foil underwent significant performance fluctuations due to the wake of the fore foil. During the favorable and unfavorable wake–foil interaction period, the pitching motion of the aft foil resulted in power extraction and consumption. As another energy source from ocean, Cui et al. [13] reviewed CFD studies to assist in the design of an oscillating water column (OWC) that harvests wave energy via onshore structures. Axial-flow self-rectifying turbines in reciprocating airflows play a key role in energy extraction. Current CFD developments in modeling, optimization, and performance improvement for OWC axial-flow turbines were summarized. Recently, a flow-induced vibration energy harvester was developed as a small-scale energy-capturing device. Wang et al. [14] reviewed current flow-induced vibrations, including vortex-induced vibrations, galloping, flutter, and buffeting, for harvesting wind and hydro energies. The current research orientation is directed toward the optimizations of structures and mechanical designs for performance improvement under extended operation conditions. The development of nonlinear technologies for adding random excitation and integration with hybrid energy-capturing devices has been proposed to increase the efficiency and power density of vibration energy harvesting. Shoele and Mittal [15] studied the flow mechanisms of the coupled fluid–structure–electric interaction of an inverted piezoelectric flag to explore the dynamics of the flow–structure interaction and its energy harvesting performance. The simulation results affirmed the large-amplitude vibrations over a wide range of parameters, as well as evidence of lock-on between the flag flutter and the intrinsic wake shedding phenomenon. A dynamic state with large symmetric flutter was found to be the most promising energy-harvesting mode with the maximum energy efficiency of about 7%. More recently, Mathai et al. [16] studied the kinematics, dynamics, and flow fields generated by an oscillating, compliant membrane hydrofoil for extracting energy from a uniform water stream. Up to 160% higher power extraction was achieved when compared to a rigid, symmetric hydrofoil by utilizing the passive compliance of soft materials interacting with fluids.

Green energy usage can help reduce carbon oxide emission. Similar to wind and hydro energies, hydrogen fuel offers no harmful emission. Hwang et al. [17] presented a comprehensive discussion on current developments in hydrogen production, storage, and utilization and its potential role in power generation and transportation systems using fuel cells, gas turbines, and internal combustion engines. In regard of hydrogen utilization, the most noticeable application is fuel cells. A hydrogen fuel cell also diminishes the usage of toxic materials typical in a battery. Among the various fuel cell types available, polymer-electrolyte-membrane fuel cells (PEMFCs) and their derivatives with low operating temperature and high-energy efficiency have attracted many applications. The performance improvement of a PEMFC requires multiphysics couplings, including electrochemistry, transport phenomena in porous media, and material science. Siegel [18] presented a comprehensive literature review on computational heat and mass transfer models in PEMFCs. A 3D model for predicting the transport phenomena was suggested for gas channel layout and design purposes. As the formation of hydrogen and oxygen bubbles affects the efficiency of PEMFCs, the bubble behaviors were comprehensively studied under the framework of transport phenomena. In general, the rapid detachment of bubbles from an electrolytic system is beneficial for performance improvement. Struyven [19] reviewed the interactions between electrogenerated bubbles and microfluidic phenomena in PEMFCs. The current knowledge on the nucleation, growth, and detachment of electrogenerated bubbles from an electrode surface, as well as the interdependent microphenomena in bubble behaviors, was summarized [19].

The blooming research on renewable energy and heat engines, as well as the need to resolve current engineering and environmental problems, has urged the development of fundamental and applied studies in fluid mechanics and transport phenomena. In this Special Issue, the relevant subjects in different fields of transport phenomena are explored by means of theoretical, experimental, and numerical methods. Two theoretical attempts are presented that are relevant to these subjects.

Malkovsky et al. (contribution 1) adopted filtration equations that consider the variation in the properties of flowing gas with temperature and pressure to modify the pulse decay method for measuring the permeability of a rock to water and the Klinkenberg constant as an effective method for measuring anisotropic permeability.

Gladkov et al. (contribution 2) proposed a mathematical model of droplet evaporation to estimate the optimal droplet size in extinguishing flammable oil transformers. The focused transport phenomena involve the liquid-to-vapor phase transition. Instead of employing an empirical or semi-empirical approach, the kinetic approach was employed to derive the governing equations using the law of conserving the full power of a vapor–liquid system. The proposed evaporation theory of a finely dispersed medium permits the analytical description of the dynamics of evaporative droplet motion in a high-temperature medium. Based on these analytical equations, the numerical estimations of the droplet size and initial jet velocity corresponding to the experimental conditions were reported.

Experimental methods have also been used to assess and improve the aerothermal performances of flow devices. Two papers are presented on this subject.

Martínez et al. (contribution 3) recently devised a variable orifice flow meter that exhibits the non-linear and linear variations of flow rate with pressure drop. The devised flow measurement system and its methodological approach are practical tools for performance assessment of variable orifice flow meters in medical applications.

Fernández-Gutiérrez et al. (contribution 4) utilized a deflector to streamline the ram airflow from the upwind suction of a vehicle to its rear where the airflow was expelled to establish a favorable pressure gradient to assist propulsion and reduce fuel consumption. The wind tunnel test results verified that the pressure gradient assisted propulsion when the airflow moved through the deflector in the model car.

Current advancements in computational fluid mechanics (CFD) have extended the investigations of the transport phenomena. Four and three studies presented in this Special Issue numerically explored the flow mechanics without and with heat transfer, respectively.

Tomescu et al. (contribution 5) implemented CFD techniques to improve the configuration of a gas–oil separator. Two separator geometries with different pitches of the cyclone from the inlet subdomain were studied. The predicted performances based on their design and CFD simulation stages were verified by the experimental results, which showed the notably enhanced overall oil retention performance.

Due to the lack of a generalized model for grid generation in CFD applications Bryzgunov et al. (contribution 6) explored the relations between the prior estimation of the parameters for grid generation and the hydrodynamic predictions of channel flows by introducing a generalized grid convergence criterion for a channel flow at high Reynolds numbers. A channel with a sudden expansion or contraction and diffuser channels with different opening angles were analyzed. The generalized criterion correlations for identifying the dimensionless linear scales of grid elements relative to the hydrodynamic signatures of the channel flow were discovered.

The following two studies utilized CFD as a design tool for energy saving and harvesting:

Wu et al. (contribution 7) designed a hull-mounted sonar dome of a ship using Open FOAM to explore the bulbous bow effect at cruise speed in calm water. With a forward length of 7.5% in ship length for the sonar dome, a reduction of 17% in resistance was achieved due to the reduced form and viscous drags, together with a 90 deg phase-lag reduction in bow wave amplitude. The relevant flow physics of these drag reductions were studied.

Douvi et al. (contribution 8) numerically examined the aerodynamic performance of a horizontal-axis wind turbine running in a dusty environment. Within the rotating frame of reference for the turbine blades, dust was added using a discrete phase model along with an SST k–ω turbulence model for airflow. The CFD simulations depicted the pressure contours, particle (dust) dissipation rate, and erosion rate on both sides of the rotating blade to estimate the deteriorated aerothermal performance owing to dust deposition on the blades.

In terms of heat transfer, the three studies described below, respectively, explored the thermal fluids for heat exchangers, solar energy collectors, and electronic equipment cooling with repeated blocks; the free convection with solid–liquid phase change; and the thermal field of a whole-body cryostimulation chamber without or with individual(s).

Jue et al. (contribution 9) analyzed the heat transfer enhancement in a duct with repeated heated-blocks subjected to periodic boundary conditions using a semi-implicit projection finite element method with the element-by-element treatment via a preconditioned conjugate gradient solver. With the streamwise rectangular slabs at the upwind locations above the repeated blocks on the heated duct wall, the heat transfer enhancement was achieved at the cost of increased friction factor. The geometry with a rectangular slab above every two adjacent blocks resulted in the highest thermal performance coefficient among the comparative groups.

Rosa et al. (contribution 10) simulated the melting and solidification process of RT28HC phase-change material under a free convective condition. The additional heat source method in conjunction with Boussinesq approximation was adopted to estimate the latent heat of the phase-change material in an enclosure that underwent independent heating and cooling processes. The thermal fields, melted fraction, and fluid motions during the phase-change process were predicted. The fluid motions were driven by the buoyancy forces due to the gradients of the fluid temperature. The free convective heat transfer rate played an important role in predicting its thermal energy storage capacity.

Elfahem et al. (contribution 11) unraveled the thermal field in a whole-body cryostimulation chamber with zero, one, or several individuals using the combined numerical and experimental method. A higher number of individuals inside the chamber raised the chamber's average temperature, thus demonstrating a more heterogeneous thermal characteristic that varied with the number of individuals. The airflow temperature gradient and heterogeneity both increased with the number of occupants. With three occupants in the cryostimulation chamber, the duration of cold exposure needed to be extended to acquire a dose/effect ratio and analgesic threshold equivalent to the one-person scenario.

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