Proceedings of the 4th World Congress on Momentum, Heat and Mass Transfer (MHMT'19)
Rome, Italy – April 10 - 12, 2019
DOI: TBA

Flow Boiling Heat Transfer and Two-Phase Flow of Carbon Dioxide: Fundamentals, Mechanistic Models and Applications

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As a natural working fluid, carbon dioxide (CO_2 or R744) has been receiving renewed interest as an efficient and environmentally safe fluid in many engineering applications including mobile air conditioning, refrigeration and heat pump systems, and various thermal energy systems such as geothermal utilization, power generation system, cooling technology for particle accelerator and other industrial applications. In order to design evaporators for these thermal systems effectively, it is essential to understand the fundamentals and mechanisms of flow boiling heat transfer, flow patterns and two-phase flow characteristics of CO_2 inside horizontal tubes including both the macro- and micro- channels. Furthermore, the proper prediction models for flow boiling heat transfer and two-phase pressure drops should be relevant to the physical mechanisms and corresponding flow patterns. This keynote lecture presents a comprehensive review of flow boiling heat transfer and two-phase flow of CO_2 characteristics and prediction methods. First, the review addresses the extensive experimental studies on flow boiling heat transfer and two-phase flow in macro-channels and micro-channels. Then, it presents the macro- and micro-scale heat transfer prediction methods for CO_2 and comparisons of these methods to the experimental database. The studies of CO_2 two-phase flow patterns are summarized and compared to some of the leading flow pattern maps as well. Furthermore, the effects of oil on the flow boiling heat transfer and two-phase pressure drops are analyzed. Due to its low critical temperature (T_{crit} = 31.1°C) and high critical pressure (p_{crit} = 73.8 bar), CO_2 is utilized at much higher operating pressures compared to other conventional working fluids. The higher operating pressures result in high vapor densities, very low surface tensions, high vapor viscosities and low liquid viscosities and thus yield flow boiling heat transfer and two-phase flow characteristics that are quite different from those of conventional working fluids. High pressures and low surface tensions have major effects on nucleate boiling heat transfer characteristics and previous experimental studies have shown a clear dominance of nucleate boiling heat transfer even at very high mass flux. Therefore, CO_2 has higher flow boiling heat transfer coefficients than those of conventional working fluids at the same saturation temperature and the available flow boiling heat transfer correlations generally underpredict the experimental data of CO_2. In addition, experimental studies have demonstrated that dryout may occur at moderate vapor quality in CO_2 flow boiling, particularly at high mass flux and high temperature conditions. Significant deviations for the flow patterns of CO_2 compared with the flow pattern maps that were developed for other fluids at lower pressures have been observed as well. The generalized mechanistic models for flow boiling heat transfer and two-phase pressure drops of CO_2 and a new flow pattern map specially for CO_2, which cover both macro- and micro- channels developed by Cheng et al. are presented and compared to the experimental data in the literature. It has been proved that the models and flow maps favorably agree with the experimental data by many researchers. In the application aspect, some simulation results for cooling of electronic chips are presented. Further fundamental research and applications are discussed as well.

Keywords: Carbon dioxide, flow boiling, two phase flow, flow patterns, heat transfer, flow pattern map, pressure drop, dryout, mechanisms, mechanistic model and applications