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Research Paper

Experimental and numerical studies of heat transfer and friction factor of therminol liquid phase heat transfer fluid in a ribbed tube

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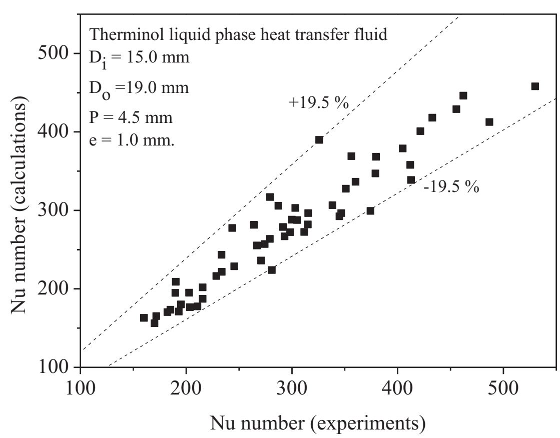
HIGHLIGHTS

- Nusselt number of Therminol 55 liquid phase heat transfer fluid is measured.
- Friction factor of Therminol 55 liquid phase heat transfer fluid is measured.
- Correlations for Nusselt number and friction factor are proposed in the ribbed tube.
- Thermal performance enhancement factor and synergy angle are predicted.

GRAPHICAL ABSTRACT



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ABSTRACT

Experiments and numerical simulations on heat transfer coefficient and friction factor of Therminol 55 liquid phase heat transfer fluid have been conducted in a ribbed tube with outer diameter and inner diameter of 19.0 and 15.0 mm, and pitch and rib height of 4.5 and 1.0 mm, respectively. Experimental results show that the heat transfer and thermal performance of Therminol 55 liquid phase heat transfer fluid in the ribbed tube are considerably improved compared to those of the smooth tube when the Reynolds number ranges from 500 to 11,500. Compared to the heat transfer in the smooth tube, the heat transfer in the ribbed tube increases by 3.3–4.6 times for the laminar flow and by 1.9–3.8 times for the turbulent flow. In addition, the measured pressure drop results reveal that the average friction factor in the ribbed tube, as compared to that in the smooth tube, increases by 2.0–3.1 times for the laminar flow and by 3.0–3.9 times for the turbulent flow. Numerical simulations of three-dimensional flow behavior of Therminol 55 liquid phase heat transfer fluid are carried out using FLUENT code in the ribbed tube. The numerical results show that the heat transfer of ribbed tube is improved because vortices are generated behind ribs, which produce some disruptions to fluid flow and enhance heat transfer compared with smooth tube. The studies of three-dimensional flow structure including distributions of velocity, temperature and turbulent kinetic energy and dissipation rate are carried out. The numerical results prove that the ribbed tube can improve heat transfer and fluid flow performances of Therminol liquid phase heat transfer fluid.

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1. Introduction

Heat transfer enhancement techniques are used to improve the overall thermal-hydraulic performance of heat exchangers in order to reduce the heat exchanger size and the cost of operation. In general, there are two methods including active method (requires external power source) and passive method (does not require external power source) used in the industrial applications. In the passive method, the mechanism for improvement of heat transfer performance is promoting the turbulence near the tube wall surface to reduce the thermal boundary layer thickness by a chaotic mixing of fluid by means of a finned tube, tube with rib, corrugated tube, helical tube and elliptical axis tube, etc., and reviewed by Popov et al. [1], Mohsen et al. [2] and Kareem et al. [3]. Among the modified tubes, the ribbed tube becomes important for the heat transfer enhancement in a single phase flow as the pressure drop increment is fairly reasonable [4]. Various researchers have experimentally studied heat transfer to supercritical water in ribbed tube under different operating conditions, as shown in Table 1. Li et al. [11] simulated flow and heat transfer of supercritical water in vertical upward internally ribbed tube. The effects of rib geometries on heat transfer of supercritical water were studied at different pressure and mass velocity. Simulations showed that the internal ribs can more efficiently improve heat transfer of supercritical water in ribbed tube. On the other hand, for water as a working fluid, Ibrahim et al. [12] measured heat transfer and pressure drop to investigate the fluid flow characteristics in a rifled tube. Experiments showed that the rifled tube has heat transfer efficiency higher than that of the smooth tube. Analysis indicated that the pressure drop and the energy consumed by using the rifled tube were also less than that of the smooth tube. An equation for predicting the average heat transfer coefficient of the inner helically ribbed tubes was presented by Ji et al. [13] based on Gnielinski equation with the friction factor in the fully developed flow region. Since the friction factor was easier to be measured, the proposed correlation equation was practically very applicable for the engineering design. The effects of internally ribbed tube on heat transfer and flow characteristics of supercritical water were studied numerically [14]. Simulated results showed that the heat transfer coefficient and pressure loss of supercritical water increased with the increase of mass flow and heat flux. These experiments and numerical simulation investigations mentioned above indicate that the ribs can indeed enhance the heat transfer performance in the ribbed tubes.

For air, refrigerants, flue gas and kerosene as working fluida, the internally-ribbed tubes play an important role in the design of the heat exchanger systems. Olsson and Sunden [15] measured heat transfer performance of two ribbed radiator tubes with airflow and constant wall temperature. The air heat transfer data were taken along the tube length. Experimental results showed that the friction factors in the ribbed tubes were higher than that in the smooth tube at both laminar and turbulent regions. The heat transfer was measured by Milman and Aleshin [16] in a model of an air condenser with an exhaust shaft during the natural convection of cooling air in the ribbed tube bundle. The correlation of heat transfer coefficient was presented for calculating heat transfer. Numerical calculations of heat transfer enhancement in a tube with triangular cross sectioned ribs were performed with FLUENT 6.1.22 code [17]. Air was selected as working fluid. The results were compared with those from the experimental studies in order to validate the numerical method. The variations of Nusselt number and friction factor were presented for the tube with triangular cross sectioned ribs. Numerical simulations of turbulent flow and heat transfer of cryogenic methane were investigated by Xu et al. [18] in ribbed cooling tubes. They found that the heat transfer deterioration of cryogenic methane at a supercritical pressure which occurs in a smooth cooling tube was weakened in a ribbed cooling tube. These results revealed that a ribbed tube surface leads to significant heat transfer enhancement of cryogenic methane. The heat transfer characteristics of R-134a were measured by Lee et al. [19] in a vertical rifled tube. The measured results were compared to heat transfer of R-134a in a smooth tube. They found that the wall temperatures of the rifled tube were much lower than for the smooth tube at the same conditions because of the swirl flow caused by the rib. The flow boiling heat transfer enhancement of kerosene as working fluid with ribbed tube was measured by Cheng et al. [20] at different heat fluxes. The measured heat transfer coefficient in the ribbed tube was compared to that in the smooth tube. A correlation of flow boiling heat transfer coefficient of kerosene was proposed for the ribbed tube. Experimental results and numerical simulations mentioned above indicate that the ribbed tube can enhance heat transfer characteristics of the different working fluids in laminar and turbulent flows.

Heat transfer fluid selection is an important factor to maximize heat transfer while minimizing pressure drop and keeping the size and weight of heat transfer equipment as small as possible. Commonly the heat transfer fluids used include water, air, glycol–water mixtures, poly alkylene glycols and hydrocarbon oils. Although there are a variety of available heat transfer fluids that meet the needs of industry, problems like limited temperature range, low heat transfer rates and high pressure drop, safety and suitability for specific applications still persist. Therminol liquid phase heat transfer fluids are widely used in the applications of energy saving and waste heat recovery, including solar thermal central receiver systems, chemical industry, pharmaceutical manufacturing, food processing and thermal engineering [21]. Therminol liquid phase heat transfer fluids provide high performance and stability in systems with operational temperatures from −73 to 400 °C. Yu et al. [22] conducted heat transfer experiments using the particular copper-in-Therminol 59 nanofluids. They measured Fanning friction factors and heat transfer coefficients of the copper-in-Therminol 59 nanofluids at different volume fractions of copper particles. Experimental results showed that the heat transfer coefficients of the copper-in-Therminol 59 nanofluids are improved for high temperatures. Selvan et al. [23] studied the dynamic behavior of a packed bed thermal energy storage system which was composed of spherical capsules of encapsulated phase change material and Therminol 66 heat transfer fluid. The influence of fluid temperature and fluid flow rate on the thermo-hydrodynamics of the solar electric generation system was investigated. Kumar and Reddy [24] predicted the influence of fluid properties of Therminol-VP1 on overall heat

Table 1
Range of investigated parameters for flow of supercritical water in internally ribbed tubes.

Investigator	Working fluid	G, kg/(m^2 s)	q, kW/m^2	p, MPa	Empirical correlation
Ackerman [5]	Supercritical water	404	315, 730	24.82	–
Suhara et al. [6]	Supercritical water	800–2000	384	27.4	–
Wang et al. [7]	Ultra-supercritical water	450–1800	200–600	25–34	Yes
Wang et al. [8]	Supercritical water	600–1250	150–650	12.6–29	–
Yang et al. [9]	Supercritical water	230–1200	130–720	12.0–30	Yes
Pan et al. [10]	Supercritical water	232–1200	133–719	12.0–30	Yes