International Journal of Heat and Mass Transfer 128 (2019) 783–793

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Experimental investigation of condensation heat transfer and pressure drop of R-134a flowing inside dimpled tubes with different dimpled depths

Kanit Aroonrat [a,b], Somchai Wongwises [b,c,*]

[a] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok, Thailand
[b] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok, Thailand
[c] The Academy of Science, The Royal Society of Thailand, Sanam Suea Pa, Dusit, Bangkok 10300, Thailand

ARTICLE INFO

*Article history:*
Received 27 June 2018
Received in revised form 8 September 2018
Accepted 10 September 2018

*Keywords:*
Condensation
Heat transfer
Pressure drop
Dimpled tube

ABSTRACT

An experimental investigation is conducted to determine the effect of dimpled depth on the condensation heat transfer coefficient and pressure drop of R-134a flowing inside dimpled tubes. The test condenser is a double tube heat exchanger where the refrigerant flows inside and water flows in the annulus. The inner tube is a 1500 mm long and 8.1 mm inside diameter. The experiments are carried out for one smooth tube and three dimpled tubes having dimpled depth of 0.5, 0.75, and 1.0 mm. For each test tube, several test runs are performed over mass flux range of 300–500 kg/m$^2$s, heat flux range of 10–20 kW/m$^2$, and condensing temperature range of 40–50 °C. The experimental results reveal that the dimpled tube presents the significant heat transfer enhancement and pressure drop penalty. The tube with the highest dimpled depth yields the highest heat transfer enhancement and pressure drop penalty up to 83% and 892% higher than those of the smooth tube, respectively. Additionally, the overall performance of dimpled tube is evaluated in term of efficiency index. The new correlations including the effect of dimpled depth, dimpled pitch, and helical pitch on the Nusselt number and friction factor of R-134a in dimpled tube are developed.



## 1. Introduction

Heat exchanger is an essential part of many operations in numerous industrial fields such as refrigeration and air-conditioning systems, refinery and petrochemical plant, power plant, and food industry. Over the years, various techniques for enhancing the heat transfer have been rapidly developed and generally employed in many heat exchanger types, which improves the heat transfer performance. The simplest technique that can be used without modifying of existing heat exchanger is the installation of the inserts into the tube. Besides the use of insert, the replacement of smooth tube by the enhanced heat transfer tube in conventional heat exchanger can be accomplished with no change in original tubing connections. However, the utilizing of heat transfer enhancement technique should be weighed between the economic advantage on plant operation and the additional cost relative to the smooth tube. On the other hand, the use of enhancement technique might be limited by the specific application. For example, the wire coil insert is not acceptable in the food industry due to hygiene problems. In the refinery and petrochemical plant, mechanically deformed tube should not be applied because of safety considerations [1]. For refrigeration system, the tube with surface modification is typically used as tube in condenser because it provides effective heat transfer augmentation and a little increase in pressure loss. While, the utilizing of swirl flow devices (e.g. twisted tape insert) presents a drastic increase in pressure drop, which is undesirable. The tube, which the surface is modified, is usually mentioned to as enhanced tube. There are many kinds of enhanced tube which one of is dimpled tube. The protuberances on the inner surface of this kind of tube can enhance the heat transfer coefficient via producing secondary flows, disrupting the boundary layer of the fluid, promoting mixing and turbulence of the flow, and increasing the heat transfer area. These factors lead to an improvement of thermal performance of condenser.

* Corresponding author at: Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok, Thailand.
*E-mail address:* somchai.won@kmutt.ac.th (S. Wongwises).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.039
0017-9310/

**Nomenclature**

| | |
|---|---|
| $A$ | surface area of the test section, $m^2$ |
| $c_p$ | specific heat at constant pressure, J/kg K |
| $D$ | tube diameter, mm |
| EI | efficiency index |
| $e$ | depth of dimple, mm |
| $f$ | friction factor |
| $G$ | mass flux, $kg/m^2$ s |
| $h$ | heat transfer coefficient, $W/m^2$ K |
| $i$ | specific enthalpy, J/kg |
| $i_{fg}$ | specific enthalpy of vaporization, J/kg |
| $k$ | thermal conductivity, W/m K |
| $L$ | length of test tube, m |
| $m$ | mass flow rate, kg/s |
| *Nu* | Nusselt number |
| $o$ | diameter of dimple |
| $P$ | pressure, Pa |
| $p$ | helical pitch, mm |
| $Q$ | heat transfer rate, W |
| $q''$ | heat flux, $kW/m^2$ |
| *Re* | Reynolds number |
| $T$ | temperature, °C |
| $x$ | vapor quality |
| $z$ | dimpled pitch, mm |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | void fraction |
| $\mu$ | dynamic viscosity, kg/m s |
| $\theta$ | helix angle, deg |
| $\rho$ | density, $kg/m^3$ |
| $\Delta P$ | pressure drop, Pa |

*Subscripts*

| | |
|---|---|
| A | accelerational |
| avg | average |
| d | dimpled tube |
| eq | equivalent |
| F | frictional |
| G | gravitational |
| g | gas/vapor |
| i | inside |
| in | inlet |
| l | liquid |
| o | outside |
| out | outlet |
| PH | pre-heater |
| ref | refrigerant |
| s | smooth tube |
| sat | saturation |
| TP | two-phase |
| TS | test section |
| w | water |
| wi | inner wall |

Over the years, several experimental studies on heat transfer enhancement technique have been reported by many researchers. Some researches focused on utilizing of coiled tube, micro-fin tube, and corrugated tube to improve the heat transfer of refrigerant during condensation process inside the tube, for example, in Refs. [2–9]. However, there have been very few works concerning with condensation heat transfer and flow characteristics of refrigerant inside dimpled tube available in the literature, which are summarized as shown below.

Guo et al. [10] reported the experimental study on the tube side heat transfer and pressure drop of refrigerant in the enhanced tube developed by Vipertex. Enhancement characters were made up of dimples and petals. In addition, the heat transfer enhancement of herringbone tube was evaluated. The refrigerants used in this experiment were R22, R32 and R410A. For condensation, the experimental results showed that the herringbone and enhanced tubes provided the heat transfer augmentation around 2.0–3.0 times and around 1.3–1.95 times as compared to a smooth tube, respectively. Similar experimental results were reported by Kakulka et al. [11]. They noted that the enhanced tube produced by Vipertex enhanced the heat transfer performance more than 100% as compared to a smooth tube. The thermal performance of the tube, which the inner and outer surfaces were developed by using longitudinal grooves combined with dimples and embossment, were evaluated by Li et al. [12]. The refrigerant R410A was used in this investigation. For condensation, the heat transfer coefficient ratio ranged between 1.1 and 1.16. While, the pressure drop ratio ranged between 1.06 and 1.68. Recently, Li et al. [13] also conducted the research on the convective condensation characteristics of R410A in two tubes with novel surface modifications, micro-fin tube, and smooth tube. The inner surface of the first enhanced heat transfer tube consisted of dimples and petal arrays while inner surface of the second one was made using trapezoidal dimples in a grid-like arrangement. The micro-fin tube showed the best heat transfer performance with heat transfer coefficients 1.8–2.2 times as compared to a smooth tube. While, the tube made of dimples and petal arrays, and that of trapezoidal dimples in a grid-like arrangement enhanced the heat transfer up to 1.65 and 1.25 times of the smooth tube, respectively. In case of frictional pressure drop, the tube made of dimples and petal arrays produced the largest pressure drop with 2.9–4.0 times in comparison with the smooth tube. Although, the micro-fine tube and the tube made of trapezoidal dimples in a grid-like arrangement generated the pressure drop up to 2.8 and 1.95 times as compared to a smooth tube, respectively. Mashouf et al. [14] observed the flow pattern of R-600a during evaporation and condensation inside smooth and helically dimpled tubes. The inner surface of the helically dimpled tube was enhanced by a modified pattern consisting of both shallow and deep protrusions. The results indicated that the dimples had a significant impact on the flow pattern during evaporation and condensation. Inside the helically dimpled tube, the transition from intermittent to annular (or vice versa) occurred at a lower vapor quality than that of the smooth tube. Based on the same apparatus and test section used by Mashouf et al. [14], Sarmadian [15] investigated the performance of a helically dimpled tube using R-600a during condensation process. It was observed that the helically dimpled tube provided the highest heat transfer enhancement and pressure drop augmentation around 1.2–2 and 1.58–1.95 times of the smooth tube, respectively. This occurrence was observed at the vapor quality around 0.5 and mass flux of 368 $kg/m^2$ s. In the author's previous works [16,17], the performance of five dimpled tubes having different pitches of dimple and corrugation were evaluated. The refrigerant R-134a was used as the working fluid. During condensation, the highest heat transfer and pressure drop augmentation can be achieved from the tube having minimum helical pitch of 5.08 mm and dimpled pitch of