Research Article

Experimental Setup Design for Investigation of Flow Boiling Heat Transfer Characteristics of R-134a in Helically Coiled Tubes with Smooth and Corrugated Surfaces

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ABSTRACT

Helically coiled tubes with two-phase flow are widely used instruments in numerous fields such as heating and cooling, energy production industry, chemical plants, etc. In academy and industry, optimum design considering the geometrical parameters and optimum working conditions of the heat exchangers are tried to find out in order to enhance the thermal performance, since the energy used is limited and valuable. In this study, an experimental setup for the investigation of flow boiling heat transfer characteristics in shell and helically coiled tube heat exchangers is presented and the procedure of the system is introduced. This paper can be considered as a guide for the researchers willing to design an experimental setup to investigate heat transfer characteristics of any fluids in helically coiled tubes or similar ones.

Keywords: *Experimental Setup, Flow Boiling, Heat Transfer Characteristics, Shell and Helically Coiled Tube Heat Exchangers*

1.INTRODUCTION

Heat exchanger is the device that transfers heat between the fluids. The rate of the heat transfer occurringbetween the fluids and pressure drops in the fluids determine the thermal performance of the heat exchangers. In order to produce more effective heat exchangers in terms of the thermal performance, some methods are used in the literature, namely active, passive and compound methods [1]. Passive heat transfer enhancement methods arepreferred more, since the external energy supplied is not required and relatively easier to establish [2]. Modifications on the tube surface such as corrugation, dimple, protrusion, rib and micro-fin, use of inserts such astwisted tape and wire coil, helically coiled tubes, use of nanofluids are common and well-known examples of thepassive techniques [3]. Surface enhancements on the tube increase the heat transfer surface area, provide flow to pass turbulence earlier, and cause swirl and vorticities at the secondary flow region, resulting in an increase in the heat transfer rate. The geometry of the helically coiled tube (i.e., its curvature) induces secondary flows to occur due to the centrifugal force, resulting in an enhancement in the heat transfer rate. Adding a certain amount of nanoparticles into the pure base fluid enhances the thermophysical properties of the fluid such as thermal conductivity, viscosity, and density, which in general causes the heat transfer rate to increase.

Some of the recent studies on flow boiling in helically coiled tubes available in the literature are summarized as follows. Kong et al. [4] experimentally performed subcooled boiling of R-134a in helically coiled tubes with vertical arrangement. The effect of heat flux, mass flux, inlet subcooled temperature and system pressure

on the heat transfer characteristics is researched. According to their main findings, there is no significant difference in the effect of operating conditions on the heat transfer characteristics between horizontal and vertical tube orientations. Heat transfer coefficient enhances with pressure but reduces with subcooling.

Niu et al. [5] studied flow boiling in helically coiled tubes with vertical orientation. An analytical modelis developed to estimate onset of dryout quality. They theoretically analyzed parameters such as heat flux, centrifugal force, density ratio, gravity, surface tension and interfacial shear force which influence the droplet entrainment and deposition characteristics having primary effects on the liquid film dryout. Also, the influence of coil diameter, mass flux, heat flux, and system pressure on the onset of dryout quality and net entrainment rate is discussed. According to findings, onset of dryout quality diminishes with raise in mass flux, and net entrainment rate rises steadily with heat flux. In another study [6], they examined experimentally flow boiling of R-134a in vertically oriented helically coiled tube under high heat flux. The effect of thermal hydraulic parameters on the flow boiling heat transfer characteristics is presented. According to main findings, vapor quality enhances the heat transfer coefficient in low quality region under low heat flux condition, and it almost does not change in the case of high heat flux condition. Vapor quality smoothly increases the heat transfer coefficient in high quality region under high heat flux condition indicating convective boiling is weakened.

Hardik and Prabhu [7] experimentally investigated single-phase flow and flow boiling of R-123 in helically coiled tube. The influence of curvature of helical coil on two-phase pressure drop, local heat transfer coefficient and critical heat flux is studied. Heat transfer coefficient at the circumference of helically coiled tubepersists same with that of straight tube in the subcooled and nucleate flow boiling regions. Moreover, heat transfer coefficient at the outer side of the helically coiled tube is higher than that of straight tube in the convective flow boiling region. However, heat transfer coefficient at the inner side of the helically coiled tube is lower than that of straight tube. In another study [8], they analyzed experimentally flow boiling of R-123 and water in helically coiled tubes. The effect of geometrical parameters such as tube diameter and coil diameter, and operating parameters such as mass flux, heat flux, exit quality and density ratio on the critical heat flux is viewed. The collected data for critical heat flux is compared with the related correlations from the literature and a new correlation is suggested in the study.

Shah [9] conducted a comparison of data and correlations from the literature for saturated boiling heat transfer of water, refrigerants and helium in helically coiled tubes. Tube orientation, tube diameter, coil diameter, pressure and mass flux are the parameters taken into consideration. It is concluded that flow boiling heat transfer coefficient in helically coiled tubes can be estimated by reliable correlations for straight tubes, not for helically coiled tubes.

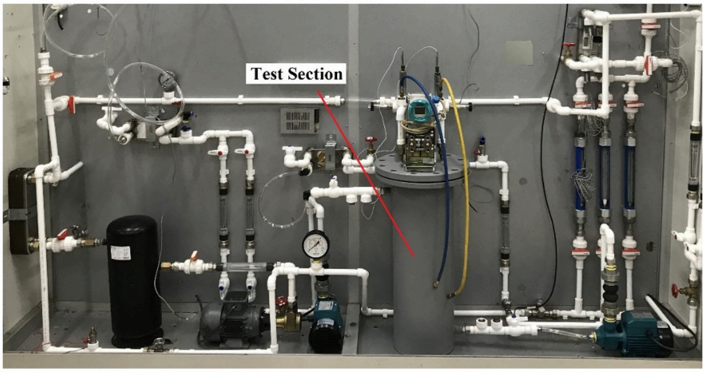
Prattipati et al. [10] numerically carried out subcooled flow boiling of water in helically coiled tubes. The influence of geometrical parameters such as tube diameter and coil diameter, and operating parameters such as inlet subcooling, mass flux and wall superheat on the axial variation of void fraction. The void fraction in axial direction increases with coil diameter. On the other hand, liquid temperature rises with decreasing coil diameter. Mass flux and curvature ratio affects the phase distribution at the same quality, whereas inlet subcooling and wall superheat do not. Correlations for vapor quality, distribution parameter and drift velocity including the effect of the curvature are proposed for estimating void fraction variation.

From the studies, it is noticed that geometrical parameters such as tube diameter and coil diameter, and operating conditions of the working fluid such as pressure, mass flux, heat flux and vapor quality have significant effect on the flow boiling heat transfer characteristics of the fluid in the helically coiled tubes.From the literature, it is noticed that there are lots of studies reported on the heat transfer characteristics of single-phase and two-phase flows in helically coiled tubes, but a few studies on two-phase flows in enhanced surfaced ones. Single-phase flows in helically coiled tubes investigated highly including with enhanced surfaces and nanofluids. For two-phase flows, studies are mostly on helically coiled tubes with smooth surface and the working fluid used in the studies is water. It is observed that there is a gap in the literature on the investigation offlow boiling heat transfer characteristics of any fluids in helically coiled tubes with enhanced surfaces such as corrugated, micro-finned, dimpled.

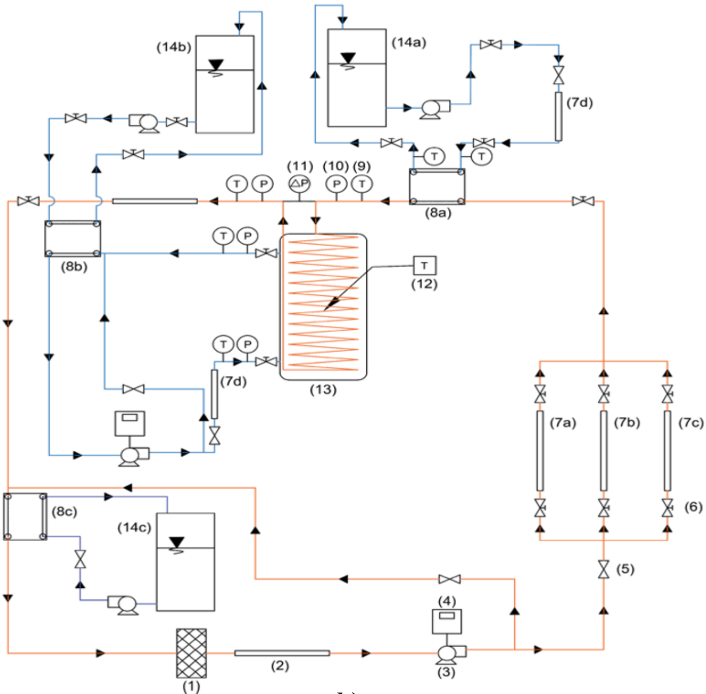
2.SYSTEM DESCRIPTION

Figure 1.a shows the picture of the experimental setup and Figure 1.b shows the schematic of the experimental setup in which blue and orange lines correspond to the fluids of water and freon, respectively. The aim of such a setup is to investigate the two-phase flow heat transfer performance of helically coiled tubes with smooth and corrugated surfaces. In addition, the names of apparatuses mentioned with numbers in Figure 1.b are given in Table 1.

Firstly, liquid R-134a is pressurized with a pump to required pressure and to determine its volumetric flow rate, it flows through one of the rotameters which is suitable in terms of measurement range. Then, it passesthrough a plate heat exchanger in which liquid hot water conditioned in the hot water tank heats the freon until it becomes saturated liquid or liquid-vapor mixture with certain vapor quality. In this section, its inlet and outlet temperatures and pressures are measured with Pt100 type RTD sensors and pressure transmitters, respectively. Also, the inlet and outlet temperatures of the liquid hot water are measured with Pt100 temperature sensors. And volumetric flow rate of the water is measured by a rotameter before it enters the plate heat exchanger. Here, vapor quality of the refrigerant can be determined precisely by energy balance equation derived for the plate heat exchanger. After it exits the plate heat exchanger, it enters the test section which is shell and helically coiled tube heat exchanger.



a)



b)

Figure 1. a) Picture of the experimental setup and **b)** schematic of the experimental setup

Table 1. List of apparatuses used in the experimental setup

#	Apparatus	#	Apparatus
1	Liquid freon tank	8	Plate heat exchangers - a) evaporator, b) heater, c) condenser
2	Sight glass	9	RTD sensor
3	Circulating pump	10	Pressure transmitter
4	Frequency converter for pump	11	Differential pressure transmitter
5	Needle valve	12	Thermocouples at 10 equally spaced locations on the outer surface of the helically coiled tube
6	Ball valve	13	Test section: shell and helically coiledtube heat exchanger
7	Rotameters with different ranges ofmeasurement	14	Water conditioning tanks - a) hot, b)hot, c) cold

Here, R-134a flows in the tube side, while liquid hot water conditioned in another hot water tankflows through the annulus. As the heat transfer occurs between R-134a and liquid hot water, refrigerant evaporatesand water cools down. Since the refrigerant flows during this evaporation process, it is called as flow boiling. In the test section, inlet and outlet temperatures and pressures of the refrigerant and inlet and outlet temperatures of the liquid hot water are measured. Pressure difference between the inlet and the outlet of the tube is also measured with differential pressure transmitter. And the temperatures are measured at 10 equally spaced points on the outer surface of the helically coiled tube by T-type thermocouples in order to determine local and average surface temperatures and heat transfer coefficients. Volumetric flow rate of the water is also measured by a rotameter before it flows through the shell side of the heat exchanger. Just after R-134a leaves the test section, its phase is observed with a sight glass to ensure it is evaporated. Then, it enters another plate heat exchanger and here refrigerant is cooled by liquid cold water conditioned in cold water tank, and the phase of the refrigerant changes to liquid again. Eventually, the closed cycle is completed. It should be noted that all the measurements are taken for specific operating conditions when the system reaches its equilibrium regime to meet steady-state conditions. This experiment is repeated for different tubes and operating conditions to investigate the flow boiling heat transfer characteristics of R-134a in helically coiled tubes and to determine the effect of using corrugated surface on the thermal performance. With the collected experimental data, proper correlations for both flow boiling heat transfer coefficient and pressure drop in the helically coiled tubes with smooth and corrugated surfaces can be proposed.

Figure 2 shows the picture of the helically coiled tubes with smooth and corrugated surfaces used in the test section.

Figure 2. Picture of the helically coiled tubes with smooth and corrugated surfaces

The tubes are made of stainless steel 316. Each of the tube has the same length (L) of 18,160 mm. Helically coiled corrugated tubes have four-start inward corrugations in the helical form on its surface. Table 2 shows the geometrical sizes of the tubes.

Table 2. Geometrical sizes of the helically coiled tubes

#	Geometry	do [mm]	t [mm]	D [mm]	phc [mm]	N [-]	H [mm]	β [°]	pc [mm]	e [mm]	α [°]
1	HCT-S	9.52	0.6	150	11.52	37	426.24	1.4	-	-	-
2	HCT-C	9.52	0.6	150	11.52	37	426.24	1.4	24	3.5	51.25
3	HCT-S	12.7	0.6	150	14.7	37	543.9	1.787	-	-	-
4	HCT-C	12.7	0.6	150	14.7	37	543.9	1.787	24	3.5	58.97

In the literature, helix angle of the coil (β) is mostly defined as the acute angle between the helix of the coil and the line perpendicular to the axis of rotation of the coil, whereas helix angle of the corrugation (α) is the acute angle between the helix of corrugation and the axis of rotation of the corrugation. Inner diameter of the tube (di) equals to envelope diameter (dn) for inward corrugation and equals to bore diameter (db) for outward corrugation. The difference between the envelope diameter and bore diameter equals to the depth of the corrugation (e).

3.CONCLUSIONS

In this study, sample of an experimental setup for investigating the flow boiling heat transfer characteristics of a refrigerant in shell and helically coiled tube heat exchangers is presented. R-134a evaporates during flowing in the tube side, while the single-phase liquid hot water cools during flowing in the shell side. Helically coiled tubes with smooth and corrugated surfaces are considered in the test section with identical geometrical tube and operating system parameters to observe the effect of enhancing the surface of the tube by corrugation on the thermal performance of the heat exchanger. The working procedure of the system is introduced, and the apparatuses used in the system is listed.

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