Applied Thermal Engineering 95 (2016) 157–164

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Numerical investigation on fin-tube three-fluid heat exchanger for hybrid source HVAC&R systems

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HIGHLIGHTS

- A simulation model of a fin-tube three-fluid heat exchanger is built and validated.
- The optimal circuit arrangement type and tube diameter are achieved.
- Applicable working condition ranges are proposed for safe running of the system.

ARTICLE INFO

Article history:
Received 22 May 2015
Accepted 30 October 2015
Available online 26 November 2015

Keywords:
HVAC&R
Three-fluid heat exchanger
Heat pump
Air conditioning
Simulation

ABSTRACT

The energy consumption of HVAC&R systems is increasing rapidly, and application of hybrid source systems is an alternative solution. Utilizing three-fluid heat exchanger in hybrid source HVAC&R system can make the system more compact in construction, higher in thermal efficiency and lower in reliability risk. In this paper, a simulation model of a fin-tube three-fluid heat exchanger is built with distributed-parameter method and validated by experimental data. Based on the demand of a new type of hybrid source system, the optimal circuit arrangement type and tube diameter are achieved. The heat transfer rates of the three fluids under different working conditions are investigated. The results also show that to ensure that cold fluid 1 is superheated in the outlet for the stable running of the system, flow rate and inlet pressure of the hot fluid and air inlet temperature should be higher than certain values, while flow rate and inlet pressure of cold fluid 1 should be lower than certain values. Air flow rate can be adjusted freely without range limit. This paper will help the design of fin-tube three-fluid heat exchanger and promote its application in HVAC&R systems.

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1. Introduction

Nowadays, Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) systems are used in a large diversity of activities. The energy consumption of HVAC&R systems accounts for more than 35% of the total electrical energy consumed in the US [1]. Utilization of renewable energy is the most effective method to reduce this consumption. However, many kinds of renewable energy are not stable and adequate enough to be used as the only energy source [2–5]. Hybrid source HVAC&R system is an ideal solution to achieve continuous working and shows great application potential; representative examples are hybrid source heat pumps [6–9] and hybrid source free cooling systems [10–12].

In order to use more than one energy sources, most hybrid source systems use two or more heat exchangers in series or parallel connection to transfer heat between three or more fluids. This kind of system has energy-saving effect while it still has the following shortcomings:

1. To achieve the utilization of multi-source, series or parallel connection of heat exchangers exists, which makes the system complex in structure [13].
2. Fluid flow inside the system is difficult to forecast due to series and parallel connection of heat exchangers, which affects the stable and efficient working [14].

Abbreviations: HVAC&R, heating, ventilation, air conditioning and refrigeration; ISMT, integrated system of mechanical refrigeration and thermosyphon.

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http://dx.doi.org/10.1016/j.applthermaleng.2015.10.158
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3. Solenoid valves are needed for switching between working modes [15], which brings reliability risk.

As we know, three-fluid heat exchanger is a type of heat exchangers that can transfer heat synchronously between three fluids. It has been used in cryogenics, aerospace and chemical industries [16,17]. The application of three-fluid heat exchangers in these fields makes the equipment more compact in construction, higher in thermal efficiency [18] and lower in reliability risk [19]. However, few three-fluid heat exchangers have been used in HVAC&R systems until now, while they show great potential in this field to overcome the above shortcomings.

Analysis of three-fluid heat exchanger was first conducted by Morley in 1933 [20]. Ever since, many researchers have developed it further. Analytical solution was obtained for special cases [21]. Finite element models were developed for some types of three-fluid heat exchangers, including co-current parallel flow [22,23], counter-current parallel flow [17,22–25] and cross parallel flow [26–28]. Integral-mean temperature difference model has also been developed to simplify the simulation of three-fluid heat exchangers [18]. Dimensionless design parameters that can be used to evaluate the performance of three-fluid heat exchangers have been studied [16,29,30]. Exergy theory and entropy generation number have been applied to describe and analyze the performance of three-fluid heat exchangers from irreversible thermodynamic theory [24,25]. However, all of the above studies only deal with heat transfer without phase change and do not include three-fluid heat exchangers that can be used for HVAC&R systems, in which two-phase fluid and air often exists.

A new type of three-fluid heat exchanger, fin-tube three-fluid heat exchanger, was proposed recently [31], as shown in Fig. 1. Its tube circuit consists of an inner tube, an outer tube and fins outside the outer tube. This type of heat exchanger can be used to achieve the heat transfer between air and two in-tube fluids. Therefore, it is suitable for application in hybrid source HVAC&R systems, such as hybrid source heat pumps and free cooling systems. However, few studies have been conducted on this new type of heat exchanger until now.

To overcome the above shortcomings of existing hybrid source systems, the authors proposed a new type of hybrid source free cooling system utilizing fin-tube three-fluid heat exchanger, called integrated system of mechanical refrigeration and thermosyphon (ISMT) [32]. The schematic diagram of the system is shown in Fig. 2. It includes two circulation loops: a refrigeration loop and a thermosyphon loop. A three-fluid heat exchanger is used to connect the two loops. The fluid in the thermosyphon loop can transfer heat with the other two fluids to achieve the simultaneous utilization of mechanical cooling source and free cooling source.

For better use of fin-tube three-fluid heat exchanger, performance investigation is essential. This paper focuses on performance investigation of fin-tube three-fluid heat exchanger for application in ISMT, a new type hybrid source HVAC&R system. A simulation model of the fin-tube three-fluid heat exchanger is built with

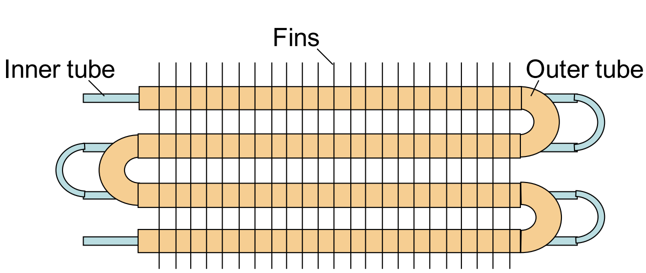

Fig. 1. Structure of fin-tube three-fluid heat exchanger.

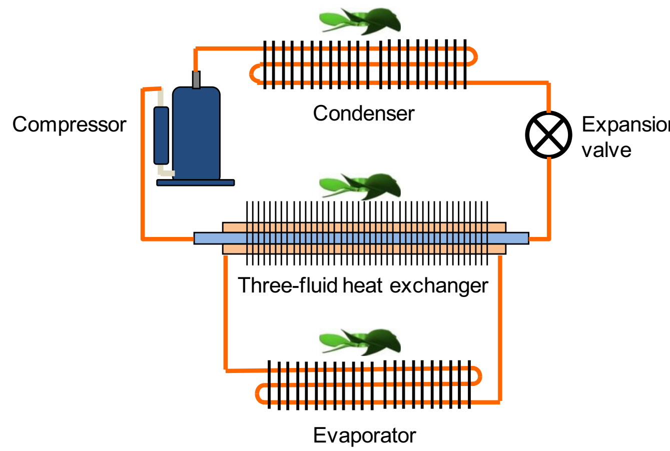

Fig. 2. Schematic diagram of the ISMT [32].

distributed-parameter method and validated by experimental data. With the validated simulation model, the performance and applicability of different structures and working conditions in the ISMT are investigated. This paper will help the design of fin-tube three-fluid heat exchanger and promote its application in HVAC&R systems.

2. Model of three-fluid heat exchanger

The flow arrangement of the fin-tube three-fluid heat exchanger in the ISMT is shown in Fig. 3. Cold fluid 1 (working fluid of the refrigeration loop) flows and evaporates in the inner tube. Cold fluid 2 (air) flows through the fins outside the outer tube. The hot fluid (working fluid of the thermosyphon loop) flows and condenses in the annular space between the inner and outer tube, cooled by the other two fluids.

The numerical model is developed with distributed-parameter method, dividing the tube circuit into elements along the axial direction as shown in Fig. 3. Each tube is divided into 30 elements. The flow chart of three-fluid heat exchanger simulation is shown in Fig. 4. The inlet conditions of the hot fluid and cold fluid 1 in one tube are the outlet conditions of the former tube in the flow circuit. The inlet air (cold fluid 2) conditions of each element in the second row along the airflow direction are the outlet conditions of the element in the same position in the first row. Compared with two-fluid heat exchangers, two heat transfer rates are needed to be supposed and two iterations are needed in each element. The heat transfer rate of the two sides in an element can be calculated as:

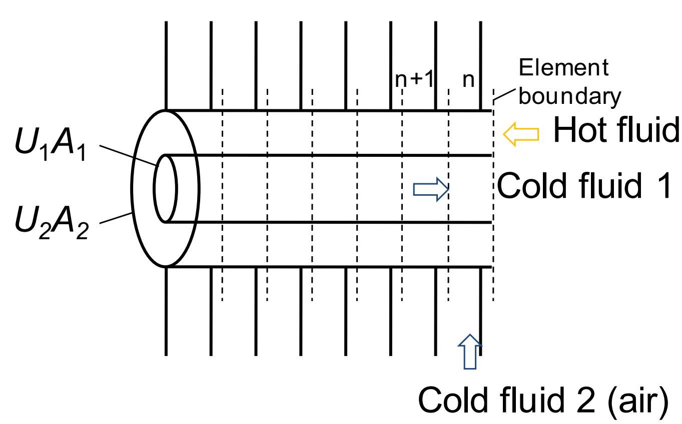

Fig. 3. Flow arrangement of one tube circuit.

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