International Journal of Heat and Mass Transfer 127 (2018) 847–855

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Theoretical study on the heat transfer characteristics of a plain fin in the finned-tube evaporator assisted by solar energy

Guodong Qiu [a], Jian Sun [a], Yuanyang Ma [a], Jiagang Qu [b], Weihua Cai [b,*]

[a] School of Energy and Power Engineering, Northeast Electronic Power University, Jilin, China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China

ARTICLE INFO

Article history:
Received 25 February 2018
Received in revised form 20 July 2018
Accepted 21 July 2018

Keywords:
Solar energy
Fin
Heat transfer
Fin efficiency
Finned-tube evaporator

ABSTRACT

Finned-tube evaporators have been widely used in air source heat pumps. Coating a solar selective absorbing coating on the fin surface is proved an effective approach to improve the heat transfer effects of finned-tube evaporators using solar energy. However, currently, most attentions were paid to the performance improvement of heat pump systems assisted by solar energy, scarce of attentions were paid to the heat transfer characteristics of this kind of fin under solar radiation. Therefore, the heat transfer characteristics of this kind of fin under solar radiation were studied using the heat transfer theory. Based on the heat transfer models, the theoretical solution of temperature field was deduced, and its accuracy was validated by numerical simulation. The effects of various factors on the heat transfer characteristics of a plain fin were theoretically analyzed. The results showed that the solar radiation would lessen the convective heat transfer capacity and fin efficiency, and even make part of solar energy to release into the environment. The maximum loss of solar energy accounts for about 12.7% of the total solar energy, and twice the fin height only generates 60% increase of the total heat transfer capacity. In the condition of larger fin height and solar radiation, the smaller convective heat transfer coefficient will produce more total heat transfer capacity. This study is helpful to analyze this kind of heat transfer problem and guide the optimization design of finned-tube evaporators assisted by solar energy.

1. Introduction

Energy has become a significant aspect affecting the sustainable development of human. With the rapid development of global economy, massive traditional energy was consumed, and the contradiction between the supply and demand of energy is becoming more and more serious. Meanwhile, with the large consumption of traditional fossil energy and the large amount of greenhouse gas emissions, environmental problems are becoming more and more serious. The limited availability of fossil energy and the intensification of environmental pollution make it very important to use a renewable energy source. The thermal energy in the ambient air is a renewable energy, which can provide a heat source for the gasification of cryogenic liquid directly in the air-bath carburetor. The air-bath carburetor uses the fin-tube structure, which is convenient to manufacture and use. So it has been widely used in the gasification of liquid oxygen, liquid nitrogen, liquid chlorine and liquid carbon dioxide. But in the cold area, the carburetor's fins are easy to frost and have poor heat transfer effects. Shi et al. [1] proposed to use solar hot water to offer a higher temperature heat source for the gasification of LPG gasification system, and a stable thermal performance was obtained.

Another important use of air heat is used as the low-temperature heat source of a heat pump for heating or making hot water. Air source heat pump (ASHP) has been widely used for its simple structure, high convenience and low cost. It plays a significant role in the exploitation of low grade renewable energy. However, in low temperature, the ASHP has low evaporation temperature, low heat production and low energy efficiency, and it is easy to frost [2,3], resulting in the decrease of heating effect. The solar energy is also a renewable energy, and it has been widely used in the heating field, such as solar water heating [4] and solar space heating [5,6]. Many researchers proposed to use solar energy to assist the operation of ASHP to improve the heating effect of the system. Sporn and Ambros [7] put forward the direct-expansion solar-assisted heat pump (DX-SAHP) system as early as 1955, and the system used solar thermal collectors as the evaporator of heat pump, which eliminated the structure of heat exchange between solar collector and evaporator, reduced the thermal resistance and improved the efficiency of heat exchange and the utilization of solar energy. Kong et al. [8] tested the hot water system of

* Corresponding author.
E-mail address: caiwh@hit.edu.cn (W. Cai).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.106
0017-9310/

Nomenclature

A_c	cross-sectional area of the fin
H	height of the fin
H_c	height of the zone without solar radiation
$H_{con=0}$	fin height which the convective heat transfer capacity is equal to zero
$H_{m,c}$	critical fin height of the maximum convective heat transfer capacity
h	convective heat transfer coefficient on the fin surface
I_{eff}	the effective solar intensity on the fin surface
L	length of the fin
m	variable, $m = [hP/(\lambda A_c)]^{0.5}$
P	circumference of the section
t_0	temperature at the fin root
t_∞	ambient temperature
t_c	temperature at the dividing line between the two parts of the fin

Abbreviations

ASHP	air source heat pump
DX-SAHP	direct-expansion solar-assisted heat pump
LPG	liquified petroleum gas
SSAC	solar selective absorbing coating

Greek letters

α	absorption ratio of solar absorbing coating
δ	thickness of the fin
η	fin efficiency
θ	excess temperature
θ_0	excess temperature at the fin root
θ_c	excess temperature at the dividing line between the two parts of the fin
λ	fin thermal conductivity
$\dot{\Phi}$	source term
$\Phi_{c,o}$	convective heat transfer capacity under the assumption that the temperature at each point of the fin is the same as the fin root
Φ_{con}	convective heat transfer capacity
Φ_{rad}	radiation heat transfer capacity
Φ_s	total heat transfer capacity of an infinitesimal dx
Φ_{tot}	total heat transfer capacity

solar-assisted heat pump. The bare flat-plate collector was used as evaporator. It was found that the system coefficient of performance (COP) could be enhanced with the increase of the solar radiation intensity or the ambient temperature. Moreno-Rodriguez et al. [9] studied the heat transfer performance of flat plate collector/evaporator of DX-SAHP system by considering outdoor temperature, wind speed and solar radiation intensity. It was found that under extreme circumstances, solar energy could effectively compensate for the heat source required by the heat pump system. Bellos et al. [10] compared energetically and financially a solar assisted heat pump heating system powered by flat plate collectors with a conventional air source heat pump system for twenty European cities. It was found that the solar assisted heating system was proved to be also the financially optimum solution for the majority of the examined cities and especially in low insulation cases. Chow et al. [11] studied the application prospect of DX-SAHP system with an uncovered solar collector in Hongkong area. It was found that this system was superior to the traditional heat pump system, and deserved further study. Kong et al. [12] analyzed the influences of refrigerant charging, compressor power and speed, collector heating time, collector efficiency, solar radiation, ambient temperature and initial water temperature on the DX-SAHP water heating system performance. Torres et al. [13] carried out the theoretical and experimental analysis of DX-SAHP. Based on the maximum efficiency of the system, the optimal evaporating temperature and condensing temperature were put forward. Ito et al. [14] analyzed the influences of collector area, the thickness of heat absorbing plate and the material selection on the performance of flat plate collector/evaporator, and provided an optimization scheme. Molinaroli et al. [15] studied energy features of a DX-SAHP, the heat pump used unglazed flat plate solar collectors as evaporator. The results allowed to state that the heat pump COP was strongly influenced by ambient temperature and solar radiation, whereas it was nearly independent on solar field surface.

In recent years, there is a relatively new method of coating a solar selective absorbing coating (SSAC) on the fin surfaces of finned-tube evaporators to assist the heat transfer, which is simple and easy to implement. Xu et al. [16] carried out the simulation and experimental research of DX-SAHP system in Nanjing in the winter environment. The system used a spiral finned-tube coated with a spectral selective absorption coating as the evaporator. The results showed that the solar finned-tube evaporator could simultaneously absorb the heat energy from the solar radiation and ambient air. The system still had a high performance coefficient under the condition with no strong solar radiation intensity and low ambient temperature. Dong et al. [17] coated SSAC on the fin surfaces of traditional ASHP evaporator, and tested it in the cold area with low solar radiation intensity. The results showed that the system was superior to the traditional ASHP under low temperature and low radiation intensity. Qin et al. [18] studied a novel direct expansion variable frequency finned solar/air-assisted heat pump system. A solar/air source evaporator-collector with an automatic lifting glass cover plate was installed on the system. The results showed that when the ambient temperature and the solar irradiation were increased, the COP was found to increase with decreasing heating time. Zhao [19] studied the conventional finned-tube evaporator and solar finned-tube evaporator under the same working condition. It was found that the heat pump system with solar finned-tube evaporator could remit the frosting problem of evaporator at low temperature and high humidity. Huang [20] compared the solar flat plate collector and the solar finned-tube evaporator under the nominal working condition. It was found that the solar finned-tube evaporator had the better heating performance under the condition without solar radiation. However, when the solar radiation was good enough, the flat plate collector had the better heating performance. Further increasing the collector area and properly increasing the fin spacing were helpful to increase the utilization ratio of solar energy.

In conclusion, for the finned-tube evaporators, coating SSAC on the fin surface can effectively improve the heat transfer and solve the frosting problem. In the existing related literatures, most of them only focused on the performance improvement of heat pump systems assisted by solar energy, and few literatures focused on the effect of solar radiation on the heat transfer characteristics of this kind of fin. The heat transfer characteristics were very significant for the optimization design of the finned-tube evaporator using this kind of fin. Therefore, this paper carried out the theoretical study on the heat transfer characteristics of a plain fin in the finned-tube evaporator assisted by solar energy. Based on the heat transfer theory, the theoretical model of heat transfer of the fin was built and the theoretical solutions of fin temperature distribution and fin efficiency were deduced. On this basis, the influences of