Applied Thermal Engineering 128 (2018) 1488–1493

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Influence of rubber ball on-line cleaning device on chiller performance

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HIGHLIGHTS

- The rubber ball on-line cleaning device can effectively remove fouling.
- The rubber ball on-line cleaning device has significant energy-saving effect.
- The economic benefit of rubber ball on-line cleaning device is very remarkable.

ARTICLE INFO

Article history:
Received 7 April 2017
Revised 21 September 2017
Accepted 22 September 2017
Available online 22 September 2017

Keywords:
Rubber ball on-line cleaning device
Fouling
Energy conservation
Economic benefits

ABSTRACT

To investigate the effect of rubber ball on-line cleaning device on chiller performance, the fouling resistance and Coefficient of Performance (COP) of a chiller have been studied experimentally with and without the rubber ball on-line cleaning device. The experimental results show that rubber ball on-line cleaning device can effectively remove the fouling on the condenser heat exchange tubes and improve chiller energy efficiency. The optimal cleaning cycle is obtained by taking minimum cost per hour as an objective function. Under the optimal operational condition, the minimum operating cost per hour is achieved and the dynamic payout period is calculated.

1. Introduction

With the expansion of building scale and improvement of demand for building comfort, building energy consumption continues to rise. According to statistics, building energy consumption accounts for 30%–40% of global primary energy consumption [1]. Among the building energy consumption, energy consumption of HVAC systems and domestic hot water system are close to 60% [2].In China, water chillers are widely used as cold sources of air conditioning systems. The production of electric water chillers was steadily growing from 2010 to 2014 [3–6]. So it can be concluded that the market of electric chillers is continually expanding, and energy-saving measures for the electric chillers have broad application.

The condenser is an important part of chiller for heat exchange between refrigerant and cooling water. The fouling will reduce the heat transfer efficiency of heat exchanger and cause economic loss. Walker et al. [7] analyzed condenser performance of coal-fired power plant, indicating that costs owing to condenser fouling were in the range of 0.4–2.2 Million (USD 2009). Xu et al. [8] demonstrated that the loss due to utility boiler fouling equaled about 0.11% of China GDP in 2000. Siddiqui et al. [9] found that fouling has a significant impact on the performance of dew-point refrigeration system. An experimental study, presented by Qureshi et al. [10], focused on the effects of condenser fouling on vapor performance. Milanovic et al. [11] carried out an experiment on fouling resistance in heat exchanger, showing that the heat transfer coefficient decreased by 510 W/(m^2·K) throughout 90-day. *ASHRAE Handbook—HVAC system and equipment* [13] reported that the energy consumption of chiller increased more than 12.4% when condenser had 0.3mm thick film-type scale. In order to solve the fouling problem in the operation of heat exchanger, various methods were used to prevent the formation of fouling. Turbulent flow in combination with moderate temperatures was used to prevent fouling [16]. Crespi-Llorens et al. [17] avoided fouling formation by scraping inner surface of heat exchange tube. Tan et al. [18] proposed solutions to eliminate fouling. Li et al. [19] developed a comprehensive approach to achieve the on-line fouling monitoring of condenser. Shen et al. [20] presented a model to predict the negative effect of fouling on enhanced tubes. Cremaschi et al. [22] focused on fouling effects on thermal and hydraulic performance

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https://doi.org/10.1016/j.applthermaleng.2017.09.113
1359-4311/

Nomenclature

Q_c	condenser heat transfer (W)
m_c	mass flow of cooling water (kg/h)
c_p	specific heat at constant pressure of water (J/(kg·K))
$t_{c,in}$	cooling water temperature inlet condenser (°C)
$t_{c,out}$	cooling water temperature outlet condenser (°C)
K	heat transfer coefficient of condenser (W/(m^2·K))
A_i	total internal surface area of heat exchange tubes (m^2)
Δt_m	logarithmic mean temperature difference (°C)
t_k	condensing temperature of refrigerant (°C)
h_w	heat transfer coefficient of cooling water side surface (W/(m^2·K))
λ	thermal conductivity of cooling water (W/(m·K));
d_i	internal diameter of heat exchange tube (m)
Re_f	Reynolds number of cooling water
Pr_f	Prandtl number of cooling water
h_k	heat transfer coefficient of refrigerant side surface (W/(m^2·K))
τ	testing time (h)
τ_1	cleaning interval (h)
τ_2	the running time of rubber ball on-line cleaning device (h)
c_e	electricity price (¥/kWh)
$t_{o,in}$	chilled water temperature inlet evaporator (°C)
P	the actual power of chiller (kW)
M_1	the increased operating costs due to fouling (¥)
M_4	running energy cost of on-line cleaning device (¥)
M	the total running cost per hour (¥/h)
P_t	the years of the cumulative discounted value appears positive (year)
b	discount value of net cash flow of the year (¥)
y	indirect measured value
f	the functional relationship between indirect measured value and direct measured value
φ	enhancement factor (1.384)
ε_n	correction coefficient of tube bundle (0.81)
g	gravitational acceleration (m/s^2)
r	latent heat of vaporization (kJ/kg)
ρ_l	refrigerant density (kg/m^3)
λ_l	thermal conductivity of refrigerant (W/(m·K))
μ_l	dynamic viscosity of refrigerant(N·s/m^2)
n_m	the average number of rows in vertical direction
d_o	outer diameter of heat exchange tube (m)
t_w	wall temperature of refrigerant side (°C)
R_f	fouling resistance of condenser (m^2·K/W)
δ	wall thickness of heat exchange tube (m)
λ_p	thermal conductivity of of heat exchange tube (W/(m·K))
$\bar{A}$	average area of heat exchange tube (m^2)
A_o	the total external surface area of heat exchange tube (m^2)
c_b	the total price of the required rubber ball (¥)
l_b	rubber ball service life (h)
P_r	servicing pump power (kW)
m_o	mass flow of chilled water (kg/h)
$t_{o,out}$	chilled water temperature outlet evaporator (°C)
M_2	the running cost of chiller (¥)
M_3	the reduced operating cost of cleaning device (¥)
M_5	the increased cost due to the replacement of rubber balls (¥)
$P't$	dynamic payout period (year)
a	absolute value of accumulated discounted value of the previous year (¥)
U_y	uncertainty of indirect measured value
x_i	the i-th direct measured value
Ux_i	uncertainty of the i-th direct measured value

of refrigerant condensers. Rubio et al. [23] compared the effectiveness of different antifouling treatments in a heat exchanger cooled by seawater.

There are countless studies on the method of removing fouling of condensers. However, most of these studies are focused on theoretical analysis or experimental model research, which have poor practicability. Compared with other descaling methods, using rubber ball on-line cleaning device has the merits of simple installation, convenient operation and strong applicability. The main objectives of this paper are as follows: (i) to design and build an experimental installation for investigating the influence of a rubber ball on-line cleaning device on chiller performance, (ii) to compare and analyze the test data (including fouling resistance, COP) of a chiller with and without on-line cleaning device and verify the cleaning effect, (iii) to do an economic analysis on the device.

2. Experimental apparatus and methods

2.1. Experimental apparatus

An experimental apparatus is designed and established. It is composed of a chiller, a rubber ball on-line cleaning device, a cooling tower, a water circulating pump, a data acquisition instrument (see Fig. 1). The on-line cleaning device consists of a ball serving device, a ball receiving device, some rubber balls and a controller. The ball serving device, mainly comprising a ball collecting tank and a water pump, is used for storing and launching rubber balls. The ball receiving device is used for collecting rubber balls. The controller is mainly used to control the ball launching time and cleaning period.

Rubber balls enter into condenser from the inlet and flow out from the exit under the pressure difference between two ends of condenser. Because the diameter of rubber ball is slightly larger than that of the inner diameter of heat exchange tube, as rubber balls go through heat exchange tube, the fouling stuck on the tube is cleaned off. Wang Q measured the friction force of a rubber ball flowing in the clean copper tube, concluding that the pressure difference required for a rubber ball smoothly passing through a heat exchange tube is about 20 kPa [32]. While the inlet and outlet pressure difference of chiller condenser is 74.1 kPa (see Table 1), which can guarantee the normal flow of rubber ball in heat exchange tubes.

In the present work, the temperature is measured by Pt100 with an accuracy of ±(0.15 + 0.002 t)°C, all temperature sensors were calibrated using the same temperature bath and same reference temperature standard before the experiment so as to reduce the uncertainty of temperature differences. Cooling water and chilled water flow rate is measured by ultrasonic flowmeter with an accuracy of ±1%, condensing pressure is measured by pressure sensor with an accuracy of ± 0.25% and the amount of electricity consumed by the compressor is measured by a three-phase watt hour meter with an accuracy of ±0.5%.

2.2. Experimental design

A water-cooled screw chiller produced by Trane Co is selected for experiment. Parameters of the chiller are shown in Table 1.