Energy Conversion and Management 95 (2015) 140–148

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental and theoretical investigation of internal two-stage evaporative cooler

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ARTICLE INFO

Article history:
Received 13 November 2014
Accepted 9 February 2015
Available online 27 February 2015

Keywords:
Evaporative cooler
Direct
Indirect
External
Internal
Saturation efficiency

ABSTRACT

The internal two-stage evaporative cooler is studied by experimentally comparing its performance with direct evaporative cooler and theoretically with direct and external two-stage evaporative coolers. The results show that the efficiency of the internal two-stage evaporative cooler is higher than that of direct evaporative cooler but it cannot be raised over 100%. It was also shown that the efficiency of the internal evaporative cooler type is less sensitive to air speed than direct type. The efficiency of the direct evaporative cooler increases by 12%, and the internal evaporative cooler increases only by 5% when fan speed switches from high to low value. The results also show that the supply air of the internal evaporative cooler has higher humidity content than direct evaporative cooler which makes it a good humidifier in cold storages where humidly close to saturation is required.

1. Introduction

Evaporative cooling systems are not new, but they have been around for centuries. However, after the advent of the mechanical vapor compression cycle, evaporative cooler has slept to lesser importance. Recently, these evaporative cooling systems have regained some momentum due to the energy conservation concern and the environmental concern of the harmful effects of refrigerants to the upper ozone layer and the global warming. In contrast to compression systems, evaporative cooling system uses water as the working fluid, which is, not only safe for use but also environmentally friendly.

Nowadays, the use of evaporative coolers for domestic air-conditioning compete well with mechanical vapor compression units because of their low energy consumption especially in many hot and dry regions such as southwestern United States, Australia, Africa, east of Asia and Arabian Gulf region. For a typical 2000-square-foot residence, the average energy consumption of evaporative cooler is as low as 250 kW h compared to 850 kW h for conventional air conditioner units, resulting in about 75% energy saving [1]. Monitoring the electricity consumption in a small commercial building of evaporative cooling systems showed considerable energy savings and improved thermal comfort compared with conventional A/C units [2].

Evaporative cooler processes are traditionally classified as direct evaporative cooler, indirect evaporative cooler and two-stage evaporative cooler, and after the recent development of M-cycle, dew-point indirect evaporative cooler has emerged as an improved version of the conventional indirect evaporative cooler. Several researchers have studied direct evaporative cooler. Fouda and Melikyan [1] developed a simplified model of direct evaporative cooler. Wu et al. [3] numerically solved the conservation equations for air and verified their results with the experimental results of Xuan [4]. Wu et al. [5] also developed a simplified model. Sheng and Nnanna [6] developed a numerical model to study the influence of the operation parameters on the saturation efficiency of a direct evaporative cooler. Their results were in agreement with many other previous studies in that the frontal air velocity and thickness of the pad module are two key factors influencing the saturation efficiency of a direct evaporative cooler. The efficiency increases with the thickness of the material pad and decreases with the increase of the air velocity. Wu et al. [5] in their simplified model and Sheng and Nnanna [6] in their numerical model show also that the inlet air dry-bulb temperature has almost no influence on the efficiency of the evaporative cooler. An experimental study was carried out by Mohammad et al. [7] to evaluate the performance of a direct evaporative cooler in humid regions. The experimental work shows that the saturation efficiency varies from 63.5% to 77.3%, and the dry bulb temperature drops to 2.1 °C at 81% relative humidity of the ambient air, and farther drops to 7.6 °C when the relative humidity is 42%.

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http://dx.doi.org/10.1016/j.enconman.2015.02.035
0196-8904/

Nomenclature

C	thermal capacity (W K^{-1})
Cp	constant pressure specific heat (J kg^{-1} K^{-1})
h_{fg}	latent heat of vaporization (J kg^{-1})
M	molecular weight (kg $kmol^{-1}$)
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (Pa)
T	temperature (K)
x	mole fraction
Greek letters	
ε	Effectiveness, $e = C_a(T_o - T_1)/C_{min}(T_o - T_w) = C_w(T_{w2} - T_{w1})/C_{min}(T_o - T_w)$
η	efficiency, $h = (T_o - T_2)/(T_o - T_{o,wb})$
ω	humidity ratio, kg_v/kg_a
subscripts	
a	air
fs	first-stage
m	mass fraction
o	outside air
s	saturation
ss	second-stage
v	vapor
w	water
1	supply condition of first-stage
2	supply condition of second-stage

The principle disadvantage of the direct evaporative cooling units is the increase of the supplied air humidity beyond the human comfort conditions, making them unsuitable to places having a high latent heat load. Even when the latent heat is low, in order to meet the sensible heat load, the supply air quantity of the evaporative cooler has to be very large to compensate for relatively high supply temperature, and can reach about 20 air change per hour [8]. This may lead to conditions of draft. In order to avoid an increase in the humidity ratio during the cooling of the supply air, an indirect evaporative cooler is introduced. Peterson and Hunn [9] and Peterson [10], based on experimental work, developed a correlated relationship for calculating the saturation efficiency of the conventional indirect-type coolers as a function of thermal capacities of the hot (outside air) and wet cold air (direct evaporative cooler supply air) streams. They indicated that the saturation efficiency increases as the thermal capacities ratio of the cold to hot streams decreases, but the low efficiency is the main disadvantage of these coolers. This is because the supply air of the indirect evaporative cooler is cooled by the supply air of the direct heat exchanger. The direct evaporative cooler has an efficiency of about 75%, and the air-to-air heat exchange has an efficiency of less than 50% [11] but it can reach about 75%, making the effectiveness of the conventional indirect evaporative unit to be in the range 37–56%. This efficiency can be improved to some extent by cooling the conventional indirect heat exchanger by water from a cooling tower. This arrangement of conventional indirect evaporative is more efficient because air-to-water heat exchanger is more effective than air-to-air heat exchanger. Crum et al. [12] use multistage indirect evaporative cooling and a cooling tower combination. By circulating the water between these units, they indicated that this combination can produce lowest temperatures and highest cooling capacities for any conditions of the intake air. Khalajzadeh et al. [13] developed a theoretical model of the two-stage indirect evaporative cooler. First-stage is a coil through which water is circulated and is cooled down by ground heat exchanger; the second stage is an indirect evaporative cooler through which water is circulated and cooled down by a direct evaporative cooler. Their theoretical results indicated that an ambient air with a temperature of 39 °C can be reduced in the first-stage to 29 °C and then in the second-stage to 23 °C, respectively, which is below the wet-bulb temperature of the air at that temperature. This means that the saturation efficiency of the direct stage is 62% implying more than 80% effectiveness of the indirect heat exchanger, which is typically higher than the effectiveness of the indirect evaporative coolers.

The restriction imposed on the temperature of the supply air, in direct and conventional indirect evaporative coolers, not to be lower than the wet bulb temperature of the ambient air has led to the use of indirect/direct two-stage evaporative cooler, and recently to the emergence of the dew-point indirect evaporative cooling system.

The two-stage evaporative cooler consists of an indirect heat exchanger and direct evaporative cooler. The first stage usually employs indirect contact cooling and the second stage uses direct evaporative cooler. The two-stage evaporative cooler was the subject of several studies. Jain [14] showed, through an experimental study, that the saturation efficiency of the two-stage evaporative cooler ranged from 1.1 to 1.2. Mohammed [15] constructed an experimental work to study the saturation efficiency of an indirect evaporative cooler (IEC) and two-stage indirect–direct evaporative cooler (IEC/DEC) under the climate conditions of Erbil–Iraq. He observed that IEC effectiveness varied between 55 and 65% and IEC/DEC effectiveness varied over a range of 90–110%. Heidarinejad et al. [16] studied the cooling performance of two-stage evaporative cooling systems under the climate conditions of some Iranian cities. It has been found that the saturation efficiency of the system varied in a range of 108–111%.

A dew-point cycle or what is known as M-cycle (Fig. 1), can overcome the above-mentioned limitations of conventional indirect evaporative cooler. In this cycle the direct and indirect cooling processes take place simultaneously. Sensible heat transfers from the air in the dry channel to water film in the wet channel causing some of the water to evaporate into the air in the wet channel. The air in the wet channel is always at a lower temperature than the air in the dry channel because it was siphon off at the outlet of the dry channel. Several studies show that the wet-bulb effectiveness of such a cycle can exceeds the 100% limit for the wet-bulb cycle devices (i.e. the conventional evaporative coolers). Anisimov et al. [17] studied numerically and experimentally indirect evaporative cooler arranged as dew-point cycle cross-flow heat exchanger. The study found that the wet bulb effectiveness ranges between 0.85 and 1.15. The study also shows that, like wet-bulb cycle evaporative cooler, dry and hot climate is best suited for dew-point cycle evaporative cooler. This result is also found by Riangvilaikul and Kumar [18] where they concluded that a counter-flow dew-point evaporative cooling system provide the comfort condition when the inlet humidity less than 11.2 g/kg. They also investigated the effect of different parameters on the effectiveness. Their results show Higher working to intake air ratio increase the effectiveness values. They recommended that the ratio of working air to intake air should be more than 35% for wet-bulb effectiveness higher than 100%. The increasing of the length of the channel increases the effectiveness by increasing the contact time and area. This last result was also found by Zhan et al. [19]