Applied Thermal Engineering 108 (2016) 398–413

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Development of porous media thermosyphon technology for vapor recovering in cross-current cooling towers

Marcia H.B. Mantelli Ph.D, Prof.

Heat Pipe Laboratory (Labtucal/Lepten), Mechanical Engineering Department – EMC, Federal University of Santa Catarina – UFSC, Campus Universitário Trindade, 88040-900 Florianópolis, SC, Brazil

HIGHLIGHTS

- Thermosyphon assisted condensers for cooling towers are developed.
- Thermosyphons transfer heat from porous media in tower plenum to the environment.
- Condenser porous media made from stainless steel curled metal stripe sponges.
- Humid hot cooling tower air percolates the cooled porous media, condensing vapor.
- Vapor condenser made of thermosyphon evaporator array in contact with porous media.

ARTICLE INFO

Article history:
Received 4 April 2016
Revised 13 July 2016
Accepted 21 July 2016
Available online 22 July 2016

Keywords:
Cooling towers
Refrigerated porous media
Thermosyphon heat exchanger
Metallic foams
Vapor recovery
Metallic stripe sponges

ABSTRACT

Cooling towers are known for their efficiency in cooling industrial water streams from moderate down to nearly ambient temperatures. However, 3–5% of the cooled water is lost to the environment in vapor phase, dragged by the air streams that exit the tower nozzles. This wasted water, usually replenished from local watershed, is being considered a major ecologic problem in some countries. The outcomes of a seven-year research, which resulted in a patent of a passive technology, designed to recover partially the vapor in wet cross-current cooling towers, is presented. The idea is to condensate vapor by removing heat from the hot air streams, using the environment as the heat sink. Two vapor condenser technologies are proposed: cooled flat plates (located after the nozzle exit) and cooled porous media, located in the cooling chamber plenum, within which humid hot air percolates before being pushed away by the fan. In both cases, thermosyphons are used to transfer heat to the ambient air, over the cooling tower. The resulting condensate is pulled to the tower bottom by means of gravity. Based on a typical year study, several numerical simulations were performed, showing that the cold plate technology is not viable. Parametric experimental studies in several porous media configurations were performed using a special setup and the best vapor recovering potential, of more than 30%, was found for stainless steel stripe commercial sponges. A prototype of the complete device, consisting of porous media plus tube arrays mimicking thermosyphons, was constructed in an especially designed reduced-scale cooling tower. The stainless steel commercial sponges attached to the evaporators of thermosyphon arrays, which condensers are located beside the nozzle exit, showed to be the best configuration for the vapor recovery device proposed, as it is passive, simple, cheap and adaptable to existing cooling towers. Although not yet optimized, the device is very promising, being able to recover, in average, 10% of the lost vapor, which is comparable with other available technologies.

1. Introduction

Water is regularly used as refrigeration fluid in industrial processes. In most industries, at the end of the production cycle, heated water is cooled down, treated and reintroduced in the plant. In large industries, such as the petrochemicals, the thermal power available in hot water streams is partially recovered by means of heat exchangers or similar devices. However, these devices are not efficient for low temperature differences between streams.

Cooling towers are often employed to cool down process water streams at moderate temperatures. Their working principles are simple and well known in the literature. The water to be cooled

E-mail address: marcia@labtucal.ufsc.br

http://dx.doi.org/10.1016/j.applthermaleng.2016.07.144
1359-4311/

Nomenclature

L/G	ratio between the mass fluxes (kg/m^2) of circulating water and dry air
T	temperature (°C)

is pumped up and distributed over filling structures, forming a down flowing cascade. These structures can be located close to the lateral walls (cross flow cooling towers) or filling the central internal area (counter flow cooling towers). A fan, located in the upper center of the device, pulls ambient air through the cascade, cooling the water. Due to gravitational forces, the cooled water flows to the bottom of the tower, where it is collected. In this process, water is lost to the environment due to the evaporation (i.e., humidification of air) or due to the dragging of small droplets by the air streams (for well-designed cooling towers, the drift rate using modern drop eliminators can be less than 0.0005% [1]). Therefore, based on mass conservation principle, this water needs to be replenished and, usually, water from local watershed is used. Taking the example of a typical refinery and a typical spring dry day within the southern hemisphere (Brazil, for instance), the volume of process circulating water needing cooling (e.g., from 42 to 27 °C) can be around 50.000 m^3/h, from which, more than 1000 m^3/h (2%) are evaporated. This means that more than 16 kg/s of water are lost to the environment, representing a volume of replacement water enough to feed a city of 250.000 inhabitants. Considering the shortage of fresh water in most of the world regions, technologies able to reduce the water lost in cooling towers are very welcome.

There are two main methods to avoid cooling towers to loose water to the environment: to cool down the hot streams before they reach the cooling towers (pinch-point technology can be useful for this purpose in large industrial plants) or to condense part of vapor contained in the humid air that leaves the equipment. Although the first idea can be very efficient and improves the energy efficiency of the plant, the small temperature differences can lead to very large and expensive heat exchangers. On the other hand, cooling towers are efficient devices that are already in use and, certainly, will continue to be applied in new plants.

In the present paper, a new recently patented passive technology, developed to recover partially the water in vapor phase that is carried out of cooling towers, is presented for the first time in the literature. Since 2006, the Heat Pipe Laboratory (Labtucal, Mechanical Engineering Department, Federal University of Santa Catarina, Brazil) is developing thermosyphon assisted equipment, designed to be installed in the plenum of wet cooling towers. In these devices, metallic porous media, through which the humid air percolates, are connected to the evaporators of thermosyphons, which conduct heat from the hot media located inside the tower to the environment, above the tower. The heat removal causes the condensation of the part of the vapor. The resulting condensed water is pulled to the bottom of the tower due to the gravity action.

The main objective of the present work is to propose a new equipment assisted by thermosyphons and porous media made from metal stripe sponges to be installed inside the cooling tower plenum, to save water in industrial plants. As this equipment is quite complex, several previous studies were performed, regarding some aspects of the equipment. A few of these works were already published in the literature (see Section 2), however, some of them did not mention the cooling tower equipment application. Therefore, in the present paper, some literature results were collected to set the background for the present proposed technology.

2. Literature review

To highlight the contributions of the present proposed technology to the state of the art, a literature review is provided. It includes, first, a brief description of advanced cooling tower technologies, being already worldwide used or under investigation. Following, it is shortly presented the state of the art of some relevant fields for the present work, including: dehumidification processes, condensation, porous media characterization, condensation within porous media, physical working principles of thermosyphons and heat transfer in finned surfaces. Actually, as already mentioned, results of some literature studies were used as "building blocks" for the proposed new technology.

2.1. Cooling towers

Cooling towers are devices able to cool down water by means of heat and mass transfer with the ambient air. To increase the contact area between air and water, sprinklers, showers and sprays can be used. Air circulates through the equipment due to natural, due to forced convection (by fans) or by both (mixed towers).

Two major heat transfer mechanisms are employed to cool down the water: convection heat transfer (when the air is colder than the water to be cooled) or liquid-vapor phase change, which is an endothermic phenomenon that absorbs energy from the water and air, causing their refrigeration. The air that crosses the tower captures the formed vapor and the resulting humid stream is expelled to the atmosphere through the fan nozzle. Therefore, the cooling tower thermal performance depends strongly of the humidity and temperature of the ambient air. Ashrae [2] affirms that, typically, for each 7 K of environment temperature variation, 1% of the water is evaporated.

According to [3], cooling towers can be classified, based on the airflow circulation mechanism employed, as **natural convection** or **mechanical draft** towers, which, in turn, can be classified as forced draft or induced (when the fan is located in the exit of the device). Cooling towers can still be classified according to the airflow: *counterflow* and *crossflow*. They can also be characterized by the method of heat transfer: *evaporative* and *dry*. In between evaporative and dry towers are the *plume abatement* and *water conservation* towers. The water cooling tower, object of the present study, has the following characteristics: mechanical draft (induced), crossflow and evaporative.

Although evaporative cooling tower was originally designed as a water conservation device [3], affirms that 3–5% of the circulating water is lost by evaporation, drift and blowdown. This is not acceptable for applications where water is scarce. In this case, water conservation cooling towers can be employed [4,5]. Besides, depending on the weather conditions, plumes can be visible [1,6,7]. In some countries such as USA, visible plumes must be avoided, due to four main reasons [7]: aesthetics, community relation, regulatory requirements and safety. Actually, visible plume is not an air pollutant as it is essentially pure water vapor made visible as mass of heated moist air leaving the tower is cooled below its dew point. The technologies employed for plume abatement and water conservation are usually the same: hybrid wet/dry cooling towers [1,6–8]. In this case, water is cooled by two heat exchangers