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Experimental study of flexible, unstructured metal foams as condensation structures

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ABSTRACT

This paper experimentally considers the use of non-structured (i.e., flexible) metal foams as a way to increase the amount of water vapor recovered from a humidified air stream. For that, a dedicated experimental setup consisting of three sub-systems (i.e., air pumping, air humidification, and air dehumidification) was developed. In the dehumidification section, different test sections (condensation structures) were installed and the amount of water recovered from the saturated air stream was recorded and correlated with each of them. Four main types of test sections were tested: (i) bare copper tube (used as base line), (ii) copper tube assisted by metal foam, (iii) finned tube and (iv) finned tube assisted by metal foam. Refrigerated fluid was circulated through copper tubes within a close loop and served as heat sink, allowing vapor phase change. The results show that the amount of water recovered increases with the surface area of the test section and with the temperature difference between the saturated air stream and the cooled surface. Also, it was shown that, above a certain quantity of metal foam within the test section, the amount of condensate produced is basically unaffected. Differently, the results indicate that the use of fins, which were properly brazed to the copper tubes, increases significantly the amount of water recovered from the saturated air stream.

1. Introduction

Removing water vapor in humid air can be important for many engineering and industrial applications, where dehumidification and/or water recovery are necessary. Basically, to remove moisture, humid air must be cooled down, so that the vapor contained in it reaches its saturated state and condensates. To be efficient, the dehumidification equipment must provide an effective and quick way to remove the condensate liquid from the environment as soon as it is formed.

Different technologies can be employed to remove moisture from humid air, such as the cold vertical plate arrangement. Under this configuration, a cooled surface is put in contact with the humid air. The humid air water vapor is partially condensed over the cooled surface and gravity is used to remove the resulting liquid. Another alternative, explored more recently, include forcing humid air streams to pass through porous media, which is cooled by flat surfaces or by serpentines.

In the present work, a novel technology is proposed and experimentally tested to partially remove water vapor from humid air. It basically consists of flexible porous-like metal foams, where a mixture of air and vapor flows through it. This media is cooled by an array of copper tubes, within which cooling water circulates. As will be discussed later, the proposed technology has many advantages when compared to the existing ones: larger contact area between cooled metal and air–vapor mixture; the porous media geometry helps the coalescence of the condensate drops in large rivulets, which facilitates gravity to pull out the liquid from the porous media; geometric flexibility and low cost.

2. Literature review

The understanding of the physical mechanisms involved in condensation is important for the design of numerous dehumidification systems. The first film condensation model was proposed by Nusselt in 1916, [1,2]. While arguably simplistic, since it relied on several assumptions, Nusselt's model served as basis for several subsequent studies e.g., [3–6], where researchers relaxed some of the original restrictions and included effects like sub-cooling, a nonlinear temperature profile, among others.

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The development of models capable of predicting the thermal-fluidic behavior of phase change processes led to the design of condensing surfaces, which play an important role in the efficiency of cold plates systems. This is because the interaction between the condensate liquid and the cold surface dictates the mode in which phase change occurs. For instance, the dropwise condensation is preferred over the film condensation, since the former is usually associated with higher heat transfer coefficients. Therefore, many researchers have directed their efforts to the development of suitable condensation promoters such as polymeric films, monolayer of organic materials and ion-plating technology. These techniques provide poor wettability of the substrate and thus dropwise condensation can be maintained for long periods [7–10].

Also, the performance of cold plates as condenser promoters is highly affected by the capacity of the liquid to be removed from the surface. This ability can be improved by the presence of grooves in the condensing surfaces. Izumi et al. [11] performed an experimental study considering the flow of saturated vapor over vertical flat plates and compared the resulting heat transfer coefficient with those obtained with horizontally and vertically grooved surfaces. As expected, the use of vertical grooves improved the heat transfer performance, as these grooves facilitated the condensate liquid to flow out of the cooled surface.

While the performance of cold plates was improved over the years, these may not be the best technology to remove moisture from humid air streams, as the plates might deflect a large amount of the vapor-air flow from the cold source limiting the contact between them. Also, when the humid air stream flows against gravity (this configuration is commonly found in vertical cooling plates subjected to an air–vapor natural convection stream) a drag effect of the uprising humid air stream over the condensed water can be observed. This effect generally increases the thickness of the condensate film reducing the condensation performance.

Therefore, based on the review above and, given the actual need of recovering vaporized water from air streams in large scale processes, an important question arises: what are the characteristics of a suitable large scale, dehumidification technology? If the pressure drop is not considered, it should be expected that a suitable technology should provide the largest contact area possible between the humid air and the cold surface and, simultaneously, allow for the easy removal of the condensed liquid from the cooled surface. Therefore, one effective way to condensate water is to force humid air to pass through a cooled porous media. This porous media should be designed not to hold the condensate, but to allow the gravity to remove the liquid from it. However, in a practical sense, the ideal dehumidification technology must provide a balance between thermal transport within the porous media, the phase-change and condensate removal from the porous media, along with the power needed to push air flow through the structure – the latter is especially relevant for large (i.e., industrial) systems.

Some initiatives regarding the use of porous media for condensing water in saturated vapor environment can be found in the literature. Renken and Raich [12], experimentally studied the forced convection heat transfer of an isothermally cooled, flat impermeable condensing surfaces, which was assisted by a relatively thin, highly conductive and permeable porous coating. The plate was placed parallel to saturated steam (vapor) flow and this combination was tested in different angles, from vertical to horizontal positions. They concluded that a thin porous media layer increased substantially the heat transfer capacity of the cooled plate. Also, the vertical position showed the best performance, as the resulting condensate layer is thinner than those observed for the other positions. Alnimr and Alkam [13] presented an analytical solution for the thickness of condensate produced over a cooled vertical wall covered by a porous media layer, in the presence of quiescent vapor. The heat transfer coefficient was also modeled while neglecting capillary forces. Wang and Beckermann [14] experimentally studied a horizontal cold plate covered with porous media. A wavy surface was used to increase the contact area between porous media and cold plate. Chang [15] in his analytical work, also considered an assembly of cold plate and porous media with the existence of three different regions: liquid film zone, two-phase zone and vapor zone, while accounting for the capillary effects, which reduced the predicted film thickness and increased the heat transfer performance. Al-Ajmi and Mosaad [16] studied numerically a vertical solid wall, which separated a cold fluid-saturated porous medium in natural convection and the condensation film in a saturated-vapor medium. The analysis revealed that this thermal interaction process is mainly controlled by the thermal resistance ratio of wall to porous-side natural convection and the relation between the condensate film convection and natural convection. In these studies [12–16], pure saturated vapor were considered.

In some practical operations, dehumidification also occurs in mixtures of non-condensable gases (NCGs) with water vapor (humid air), which, in general, deteriorates the heat transfer process due to the formation of a gas boundary layer over the condensate liquid film. Many studies dealing with the vapor condensation in the presence of NGC can be found in the literature [17–22]. Other studies investigated the condensation of vapor contained in air–vapor mixtures in vertical ascension, which reach the cooled surface from below [23–25]. Czubinski et al. [26] performed an experimental study that considered the condensation of humid air on the bottom side of flat or grooved cold surfaces and compared their results with literature models.

Although not extensively explored in the literature, metal foams can be used as porous media. The literature defines metal foams as cellular materials that have a solid structure, and are made of metals such as: bronze, copper, stainless steel, among others, although aluminum is the primary material employed (Ashby et al. [27]). Metal foams are composed by large voids, the pores, which can be or not interconnected. They are considered permeable if the pores are interconnected. The left side frame of Fig. 1 shows a picture of a typical (i.e., structured) metal foam.

In the present work, porous media composed by flexible metal foams, such as the one presented in the central picture of Fig. 1, are employed to condense vapor in humid air environment. Heat is removed by means of an array of parallel tubes in which cooling water circulates. Actually, this flexible metal foam is found in the market as domestic cleaning sponges and is composed by a thin stainless steel metal tape rolled in a spiral shape (see Fig. 1, right frame). This flexible metal foam presents several attractive characteristics: large flat area, high permeability, as the rolled tape forms small 'tubes' that allow for the coalescence of the liquid drops, geometric flexibility and low cost.

A few applications of metal foams as condensers can be found in the literature, such as moisture removal in clothes as described by Cochran et al. [28]. In this equipment, metal foams allow the humid air stream to be in contact with a cold water flux through highly porous metal foams, so that the water is able to capture condensed liquid drops. Another application of metal foams is as efficient fins in compact heat exchangers [29]. Li et al. [30] studied the performance of commercial packed beds to promote the direct contact between saturated humid air and fresh ambient temperature water. The main concern of theses researchers (e.g., [28–30]) was the retention of the condensate liquid within the porous media, which decreased the dehumidification performance.

In the present work, cooled flexible metal foams are considered as the porous media and used to partially condensate the vapor contained in humid air. Therefore, a saturated air stream crosses the porous media, which is cooled by several parallel copper tubes,