25thABCM International Congress of Mechanical Engineering
October20-25, 2019, Uberlândia, MG, Brazil

REVIEW OF MODELS AND MECHANISMS FOR FINNED-TUBE HEAT EXCHANGERS UNDER DEHUMIFYING CONDITIONS

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Abstract. *This study addresses a review of finned-tube heat exchangers focused on applications of air-conditioning, hence operating under dehumidifying conditions. According to the literature review, deviations of the order of up to 15% can be inferred among predicted values for thermal resistance in the air-side according to different models, and the same order of magnitude occurs for the mass transfer process. Several approaches present diverging conclusions about the effect of some parameters, such as fin pitch, indicating that there is no consensus about several parameters' influence. Additionally, this study aims to evaluate predictive models from the literature when compared to experimental conclusions on the effects of various parameters. The objective of this comparison is to contribute on the identification of relevant parameters of the heat and mass transfer in finned-tubes heat exchangers.*

Keywords: *finned heat exchanger, dehumidifying, air-side*

1. INTRODUCTION

Most of the commercial air conditioning systems are based on the use of finned-tube heat exchangers (cooling coils) using either cold water/brine or saturated refrigerant in order to cool down moist air to a desired temperature and humidity. The choice of this type of heat exchanger relies on a combination of its compactness, manufacturing easiness and relative low price. With the introduction and popularization of alternative sensible-only comfort-cooling methods such as chilled beams, a good understanding of the dehumidification process with existing methods and equipment becomes key to a properly operating condition of an HVAC system.

Several methods and models to predict operational parameters of cooling coils can be found in literature, with some of them incorporating the coupled heat and mass transfer. However, due to distinct approaches and hypotheses, most of the recent models report deviations generally up to 15% between estimated and experimental data for heat transfer coefficient. Deviations of the same order can be found even on experimental studies, which is generally attributed to differences in experimental data reduction methodologies (Wang et al., 2000a and Wang, 2000b). For example, Kim, Youn and Webb (1999) developed a correlation which is claimed to predict the heat transfer parameters with a claimed 20% margin. Another short paper by Wang, Lin and Lee (2000) reports a correlation with 15% of margin. Wang, Hsieh and Lin (1997) attribute inconsistencies in experimental findings primarily to the calculation of wet fin efficiency. In addition, there is a myriad of studies that investigate the effects of parameters that are not often implemented into the models. Studies focused on investigation of heat and mass transfer parameters report increments and decrements of the coil performance within this same range of variation of 15%.

The high deviations between the predicted and experimental results, and between experimental results from distinct research groups precludes a proper evaluation of actual influencing factors. In this context, several authors, such as Ma (2007) and Wang (2002), indicate through experimental results that a given parameter such as surface wettability and fin spacing can present variations on the thermal resistance in the air-side of the same order of magnitude of the deviations found in the predictive models, which emphasize the need for more reliable models and experimental results, or rather, for a better understanding of the influence of such parameters so that further empirical studies are better equipped to develop more accurate and general correlations.

Therefore, this study aims to review and analyze some of the hypotheses accounted for when modelling cooling coils.

2. COOLING COIL MODELS

2.1 Review of coil models

Kastl (2012) recently reviewed 24 cooling coil models, comprising studies since Goodman (1938) up to a more recent study presented by Xia (2009). Kastl (2012) categorized the models according to its methods and its assumptions. The methods were categorized as either LMTD (or a variation of it), ε-NTU, or a fundamental-equation based method given by ASHRAE (2009). Kastl highlighted that the revised studies considered one or more of the following assumptions: an enthalpy potential as the driving mechanism of the process, a fixed (constant) proportionality between heat and mass transfer (expressed by a unitary Lewis Number), and a fictitious enthalpy for expressing an equivalent sensible-only heat transfer. Based on four selected models, Kastl (2012) evaluates the effects of such different assumptions, and concluded that each model is affected differently by each evaluated parameter, and consequently the degree of accuracy when compared to experimental data presented distinct trends for each model, and no model could be identified as the best for all conditions. Although the author reports great agreement between the four models, especially when comparing the total coil capacity (which agreed within 2% within themselves and with a set of experimental data), a large error of latent heat capacity (up to 25%) shows that, even considering the author's own remarks that a larger error for latent heat is to be expected (because it is the smaller portion of the total heat capacity), there are still improvements to be made for dehumidification.

Jin et al. (2006) developed a simplified model based on experimental fitting for a given coil. The model is derived from fundamental equations of mass and energy conservation, whose many unknown variables are grouped into six parameters. Considering the high predictive accuracy of the model under different operational circumstances for the experimental results used in its development, even during transient conditions, an analysis of the fitting parameters can provide valuable insights into their effects.

Guilin et al. (2018) developed a model for a one-dimensional parallel-plate heat exchanger that uses the Merkel method for simultaneous heat and mass transfer, modifying it in order to account for the effects of wetted surface roughness. While this study only accounts for hydrophilic surfaces, i.e., supposes a wavy condensate film, its results considerably improve the predictability of the model when compared to the same model without the aforementioned roughness corrections, according to Guilin *et al.* (2018) own experimental work.

Pirompugd and Wongwises (2017) compared two different models and assessed their divergences among their predictions and against experimental data obtained by the authors. The first model, named by the authors actual-dry-bulb-temperature-method (ADTM), is based on an assumption by McQuiston (1975) that specific humidity can be written as a function of air dry bulb temperatures for this type of application. The second model, named by the authors equivalent-dry-bulb-temperature-method (EDTM), is based on an assumption made by Wang and Hihara (2003) that the heat and mass transfer can be expressed by an equivalent sensible-heat-only process with equivalent enthalpy differential. Both models are applied to what they call the finite-circular-fin-method (FCFM), which is essentially a method for numerically calculating the heat exchange by dividing the coil into subsections equivalent to simple finned-tubes. The authors found that the ADTM predicts a lower heat and mass transfer than the EDTM does. The authors also develop empirical correlations based on their own experimental results, and found that their proposed correlations agree with data within a 15% error band.

Pirompugd *et al.* (2008) performed a review on data reduction methodologies, and one notable conclusion presented in their article is the relatively recent consensus of a Lewis number different than unit for the air-side. The Lewis number corresponds to the ratio of heat and mass transfer coefficients.

2.2 Discussion about the models

In this review, the models can be classified roughly by their attempts to solve the complexities of this type of heat exchanger. The first complexity corresponds to the irregular flow arrangement present in a multi-pass cross-flow heat exchanger. In order to solve this aspect, the exchanger can either be considered as a single unit to which complex correlations may apply, or the heat exchanger can be divided into small parts, which are solved individually by valid predictive methods.

Alternatively, it is possible to model the system by dividing the coil into dry or wet regions. Most meaningful experimental study are performed at either fully dry or fully wet conditions, and the models try to split the coil into dry and wet segments, and to apply the correlations accordingly. This is usually done through iteration, by estimating the point at which the coil surface is colder than air inlet dew temperature, and then solving for this condition. The aforementioned aspects are well documented in Kastl (2012) review.

It is also possible to couple heat and mass transfer. In general, older models tend to avoid deeper analysis of the mass transfer, instead relying on simplifying assumptions such as a linear relation between temperature and humidity ratio. More recent models, however, aim to combine several methods to predict mass transfer.

3. PARAMETRIC ANALYSIS

3.1 Input parameters

Most of the recent studies focus on evaluation of air side parameters, such as fin geometry and operational conditions. For example, Lin et al. (2001) investigated the effects of such variables in the heat and mass transfer occurring in square fins. According to this study, the fin efficiency, which is defined based on enthalpy variation to include condensation effects, is higher for dry than wet fins, is unaffected by air inlet dry-bulb temperature, and is unaffected by inlet relative humidity for fully wet fins. Additionally, Lin *et al.* (2001) revised the effects of relative humidity of previous investigations, and concluded that most of results of available experimental studies might be affected by uncontrolled fin base temperature, as well as possible effects of fins partially wetted. One can also conclude from analyzing their data that fin efficiency increases with air velocity for dry and wet fins, with higher effect for wet fins. A study on 2D simulation of wet fins by Liang et al. (2000) found similarly that an increase of relative humidity reduces fin efficiency for partially wet fins, and has negligible effect on fully wet fins.

Mirth and Ramadhyani (1994) experimentally evaluated chilled-water cooling coils, and found out that coil heat transfer coefficient is consistently lower than laminar isothermal parallel plate flow, which is attributed to a lower mass transfer at tube wake region. This conclusion was corroborated by several studies.

Sharqawi and Zubair (2008) studied the efficiency of fin profiles, and one notable finding is a correlation between airside overall pressure and the fin efficiency, with increment of efficiency with pressure. The authors claim that this effect is related to higher humidity ratio (moisture content) at higher pressures, which increases the enthalpy potential. This effect is shown by the authors to be independent of relative humidity (at least for RH from 0.4 to 1.0), which shows that this effect is not related to increased/decreased wetting of the fin surface.

Ma et al (2007b) studied enhanced fins with hydrophilic coating and found out that for partially wet surfaces, an increase of relative humidity leads to a loss of thermal performance, and that for wavy fins, lower inlet water temperature leads to an increased j-factor.

It can be concluded based on these papers that the ratio between dry and wet area is a very important factor . This aspect is already widely known and accepted, but Kastl (2012) pointed out that this effect is accounted for by dividing the computational domain in two discrete regions. In other words, no model that predicts a smooth transition between dry and wet surfaces is available.

Additionally, the relative humidity has reduced influence for completely dry fins. This is noted by the reports of independence between performance and relative humidity for fully dry and fully wet fins, such as presented by Lin et al. (2001) and Ma et al (2007b), with a relation only appearing significantly when partially wet fins are involved.

3.2 Geometrical parameters

Bhuiyan and Islam (2016) presented a review with experimental and numerical results gathered from the open literature for several types of heat exchangers, as well as different effects and mechanisms involved in the heat and mass transfer process. One important conclusion of this review is the divergence in experimental results for the effect of fin pitch. According to Bhuiyan and Islam (2016), Elmahdy and Biggs (1979) reported increment of heat transfer coefficient with fin pitch, while Wang (1996 and 1997) reported no significant effect, and McQuiston and Tree (1971) reported an opposite effect trend.

Mirth and Ramadhyani (1994) reported that heat transfer coefficient increases with reduction of coil length, but this effect reduces with increments of Reynolds number, which was attributed to developing flow in the first row of tubes. The authors observed that heat transfer coefficient increases with fin spacing, once again with suppression of this effect for higher Reynolds numbers. The authors attribute these effects to the formation of vortices at higher Reynolds numbers. One can note that their experiments had airside Reynolds in the range of 400-2400, which is a typically laminar/laminar-turbulent-transition range.

Bhuiyan et al (2015) performed a CFD study on the effects of geometrical parameters for wavy fins in dry conditions, and it was reported that staggered tube arrangements give better thermal performance (j-factor), and wavy fin angle greatly increases dry thermal performance. Conversely, longer longitudinal and transversal tube pitch (length between tubes in air flow direction and transverse direction, respectively) tends to decrease dry thermal performance.

Ma (2007b) investigated enhanced coated fins and found out that Colburn-j decreases with increment of number of tube rows, and decreases with fin pitch increment, with this effect becoming more pronounced under partially wet conditions. Additionally, this author concluded that for fully wet wavy fins, the thermal performance of the surface increases with relative humidity, while fully wet louvered fins are insensitive to changes of relative humidity.

3.3 Other Parameters

Vikrant Aute (2016) revised air-to-refrigerant cooling coils of fin-and-tube type and microchannels, and found similar results among the different models evaluated, with the best empirical correlations claiming 2% deviation, while other models had deviations ranging from 8 to 17 %.One interesting point of this review is the potential consideration of air and refrigerant flow maldistribution, as well as methodologies to include such effects in modelling. Another relevant point is the performance degradation caused by fin-to-fin conduction, which is claimed to be on the range of 10-20% for some direct-expansion applications. It should be noted that the conclusions might not be entirely valid for chilled water coils, because this condition was not included in this review.

Another relevant line of inquiry can be taken from the review work of Nickolas et al. (2017), in which the effects of non-conventional geometric parameters as well as the effects of vortex generators on the thermal-hydraulic performance of cooling coils is evaluated. It was found that in general, the insertion of disturbance-enhancing elements such as vortex generators tends to increase heat transfer at the cost of higher pressure drop. Other modifications such as angled elliptical tubes instead of circular tubes cause lower pressure drop, while still contributing to the generation of vortices. Tang et al (2009) also studied the effects of vortex generators, and found out that vortex generators with low height, high angle of attack and high length offer the best heat transfer characteristics.

Li et al (2015) performed a CFD study on the performance of vortex generators on plain fins, and found out that longitudinal vortex generators (LVGs) can increase the thermal performance (Nusselt number) of plain fins up to 20%, and that rectangular winglets give better performance. These authors also point out that wavy fins provide greatly enhanced heat transfer performance, although overall thermal-hydraulic performance (given by a j-factor/f-factor ratio) is worse than plain fins with LVGs. Finally, Li *et al.* (2015) found that punched holes on fin surface also enhance thermal performance, more pronounced when combined with rectangular LVGs than with delta-type LVGs.

A similar line of investigation relates to the surface characteristics of the fins, because it has been reported that different cleaning products can cause different degrees of surface wettability, which in turn can radically modify the condensation mechanism, and affect the thermal-hydraulic performance of the coil (McQuiston, 1980). Hong and Webb (1999) reported no significant changes on heat transfer characteristics when coated with hydrophilic material, although one can observe their data and conclude that while small in magnitude, hydrophilic fins are consistently less efficient than uncoated ones. It has also been found that surface wettability alone does not account entirely for its effect on the heat and mass transfer, and that most notably fin pitch influences the relation between wettability and the thermal resistance (Ma 2007 and Wang 2002).

4. DISCUSSION

A common trend in published studies (Park and Jacobi, 2001) is related to using the tube outer diameter (plus fin collar, when applicable) as the characteristic length for evaluation of Reynolds number. Even though reasonable, this method does not take into account the effects that the fins might have in inducing or reducing airside turbulence, especially when corrugated fins are used. Alternatively, Mirth and Ramadyahi (1994) adopted twice of the fin spacing for characteristic length, in a similar way to hydraulic diameter during flow between two parallel plates. Zhang et al. (2015) adopted a variation of finned channel hydraulic diameter (four times area divided by perimeter). The lack of consensus on this parameter can hinder cross analysis of experimental works.

From the studies on fin pitch (fin spacing) and surface wettability (hydrophilic coatings) it can be concluded that both variables have a joint effect on the heat transfer capability of the equipment, and that this effect seems to be strongly related to the additional airside turbulence (eddies) caused by the presence of water droplets (for non-hydrophilic coated surfaces) in tightly spaced fins. This is corroborated by the conclusions presented by Wang (2002) indicating that heat transfer coefficients increases with fin spacing reduction for hydrophobic (uncoated) surfaces when compared to hydrophilic-coated surfaces, with variation up to 20% on his experiments. Similar conclusion was addressed by Ma (2007), who indicated that heat transfer is higher in conditions that dropwise condensate has more restriction to flow. The magnitude of this increase is similar to the reported effects of vortex generators. The hypothesis of turbulence caused by water droplets is also corroborated by related literature, which reports that hydrophilic coating has a significant impact on airside pressure drop characteristics. However, Wang et al. (1997) reported that experimental results by Jacobi and Goldschmidt (1990) indicated performance degradation of wet fins with increase of airside Reynolds up to 3000, and above this value the variation of heat transfer coefficient with Reynolds number is marginal. The authors attributed this degradation to condensate retention. It is not known if the condensation method is drop-wise or film-wise, but it can be noted that the effect stops at a typical laminar-turbulent transition Reynolds range.

While predictive models have in general accounted for the effects of fin pitch into consideration, the effects of surface wettability and the joint effect of fin pitch with surface wettability have not been found in any model up until the writing of this paper.

Another notable finding was presented by Zubair and Sharqawi (2008), who showed the effects of ambient pressure on fin efficiency. This is of particular importance because coils are often installed into pressurized chambers for testing and operation, and it is often installed upstream, downstream, or sometimes even between the fans. Most commonly in simpler packaged fan-coil units (FCU), it is installed upstream the fan, then. Based on Zubair and Sharqawi (2008) conclusions, this condition is subject to some deterioration of heat transfer performance due to the lower airside pressure. Additionally, the authors attribute this effect to changes in humid ratio, and consequently it corroborates the need to further study the convective mass transfer occurring in heat exchangers.

5. CONCLUSIONS

The main conclusions of this review can be listed as follows:

1- There is no consensus on the proper scaling parameters for some of the dimensionless parameters such as the Reynolds number, most notably the characteristic length in the Reynolds number. Likely due to the geometrical complexity of the exchanger.
2- Previous disagreements on the effects of parameters can indicate the influence of previously unaccounted parameters, as seems to be the case with fin spacing and surface wettability.
3- Recent studies on the effects of a myriad of parameters have been done recently, with few to none being incorporated into predictive models.

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