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Heat Transfer Modeling and Thermal Analysis for a Fluidized Bed

(Research Note)

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Abstract This paper presents a mathematical model and a computer simulation program for the numerical prediction of the performance of a fluidized bed cooling tower. The mathematical model is based on the heat and mass transfer equations. This model is used to predict the thermal behavior of a fluidized bed cooling tower with experimental data. In this paper experiments have been performed to measure the thermal performance of a fluidized bed cooling tower of 280 mm diameter. Hollow plastic spheres of three different sizes, with diameters of 20, 25 and 37 mm and particle densities ranging from 70 to 325 kg/m^3, were investigated as packing materials, and results for static bed heights of 100 mm and 300 mm are reported. Measurements were obtained at an approximately constant inlet hot water temperature of around 42°C and cover a range of water mass flux from 0.3 to 3.6 kg/sm^2. Liquid/gas ratios varied between 0.1 and 5.5. Results for thermal performance are presented showing the effects on the cooling tower characteristic, KaV/L, of the different packing elements and of varying water flow rate, air flow rate and the height of the hot water distributor above the bed. This provides a useful semi experimental relation, in the area generally lacking in design and performance data. It has been found that the accuracy of 5% obtained by using the chosen model can be then taken into account whenever this model is used to predict other characteristics related to the fluidized bed cooling tower.

Keywords Fluidized bed cooling tower, Mathematical model, Computer simulation program, Tower characteristics.

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1. Introduction

In general, the design of an efficient, compact mass transfer pack for gas/liquid applications is based on the optimization of the passage diameter and passage length. Also from a number of recent studies it is apparent that the choice of material plays a major role in packing design, the ideal material being highly formable in order to provide a high specific surface area [1].

The use of fluidized bed equipment has opened wide possibilities for insuring reliable design and improving various industrial technologies such as coal combustion, gasification and drying. The thermal performance of a fluidized bed cooling tower packing is often expressed by the dimensionless quantity, KaV/L, known as the tower characteristic, where the composite quantity Ka is the overall volumetric mass transfer coefficient, V is the volume of the packing per unit plan area and L is the liquid (water) mass flux. An alternative measure is the number of transfer units, NTU, which is simply related to the tower characteristic by NTU = (KaV/L)(L/G), where G is the gas (air) mass flux. In the fluidized bed cooling tower (FBCT), hot water is sprayed downward on to the bed of spherical packing elements in counterflow to an upward flowing unsaturated air stream that fluidizes the bed, thus creating a three-phase turbulent bed contactor characterized by large interfacial area, vigorous mixing and high heat and mass transfer coefficients. Douglas [2] reported excellent performance for the cooling and humidification of a hot wet air stream in a floating bed contactor with a packing consisting of hollow polypropylene spheres of diameter 38.1 mm and a static bed height, V, of 254 mm. Over the ranges tested, NTU was found to decrease with the increasing water or air mass flow rate. Experiments for water cooling in a FBCT, by Barile [3], covered static bed heights up to 457 mm and spherical packing diameters of 19 mm and 38.1 mm. The tower characteristic KaV/L was found to increase, albeit at a diminishing rate, with increased static bed height, and was slightly lower for the larger spheres. The measurements exhibited values of Ka, an order of magnitude higher than those for fixed packing towers. Furthermore, the data indicated that Ka decreases as V increases and increases with increase in either G or L.

Seetharamu and Swaroop [4] tested two different sizes of FBCT, with tower cross-sections 250 mm square and 1100 mm square. Extended polystyrene spheres of diameter 25.4 mm were used as the packing material and static bed heights up to 310 mm were investigated. They concluded that in comparison with conventional cooling towers, with either splash or film type fills, the FBCT requires a much lower packing height, has a comparable pressure drop and can handle higher liquid throughputs. El-Dessouky [5] experimented with a FBCT packing of 12.7mm diameter spongy rubber balls and static bed heights of 300 to 500 mm, and found that increasing the hot water inlet temperature produced a marked improvement in KaV/L. This was attributed to the increased interfacial area and gas holdup associated with the smaller air bubble mean diameter formed at higher water temperatures due to the reduction in surface tension and viscosity. This paper reports on work in progress to extend the range of experimental data available for use in the design of fluidized bed cooling towers. The FBCT tests conducted cover a larger number of spherical packing element sizes than previously considered in a single study.

2. Experimental Set-Up

The experimental tower shown in Figure (1) consists of a vertical 280 mm internal diameter transparent Perspex column having working and inlet plenum sections 1500 mm and 700 mm long respectively. The bed, comprising hollow plastic spheres, is supported on a wire grid with a free flow area exceeding 80% of the tower cross-sectional area. Hot water is introduced through a single spray nozzle mounted centrally above the bed.

The nozzle height can be adjusted to vary the extent of the freeboard region. Instrumentation includes platinum resistance thermometers for measurement of the hot and cooled water temperatures, and the dry bulb and wet bulb air temperatures at inlet and outlet. The air and hot water flow rates are measured using an orifice plate and a turbine flow meter respectively. Pressure transducers are provided to measure the bed pressure drop and the orifice plate differential pressure. All measurement outputs are connected to a data-logger linked to a personal computer for rapid data acquisition and analysis. Barometric pressure and the static pressure at the orifice plate are recorded separately. A backup system of mercury-in-glass thermometers, Rota meters, and U-tube manometers is also provided. The uncertainty associated with the PRT measurements is estimated to be less than ±0.5°C. Calibration data and manufacturers' specifications indicate that, apart from the lowest end of the test ranges, the air flow rate and water flow rate measurements are accurate to ±5%. The average energy balance error for all the tests included in this paper is 11%.

Thermal performance testing of the FBCT apparatus described above has been conducted for both the fixed bed and the fluidized bed regimes. Test data have been obtained for the following approximate ranges of operating variables: water mass flux, $L = 0.3$ to 3.6 kg/s m^2, water/air mass flux ratio, $L/G = 0.1$ to 5.5 and hot water inlet temperature, $T_w = 25$ to $55°C$.

Three different sizes of spherical packings were employed, with diameters of 37.5, 25.4 and 20 mm and respective particle densities of 69, 326 and 239 kg/m^3. The two smaller sizes are hollow polypropylene spheres and the largest size resembles table tennis balls. Tests were also made with the column empty. The static bed height was varied over the range 50 to 400 mm. In addition, two different commercial spray nozzles (Spraying Systems) were used; one with a 4 mm diameter single orifice that produces relatively coarse droplets of 2000 micron average median volume diameter, and a multi-orifice nozzle that produces finer droplets of 800 micron average median volume diameter. The height of the spray nozzle above the bed support grid, H, was varied from 400 to 1100 mm. A sample of results is presented in the following section.

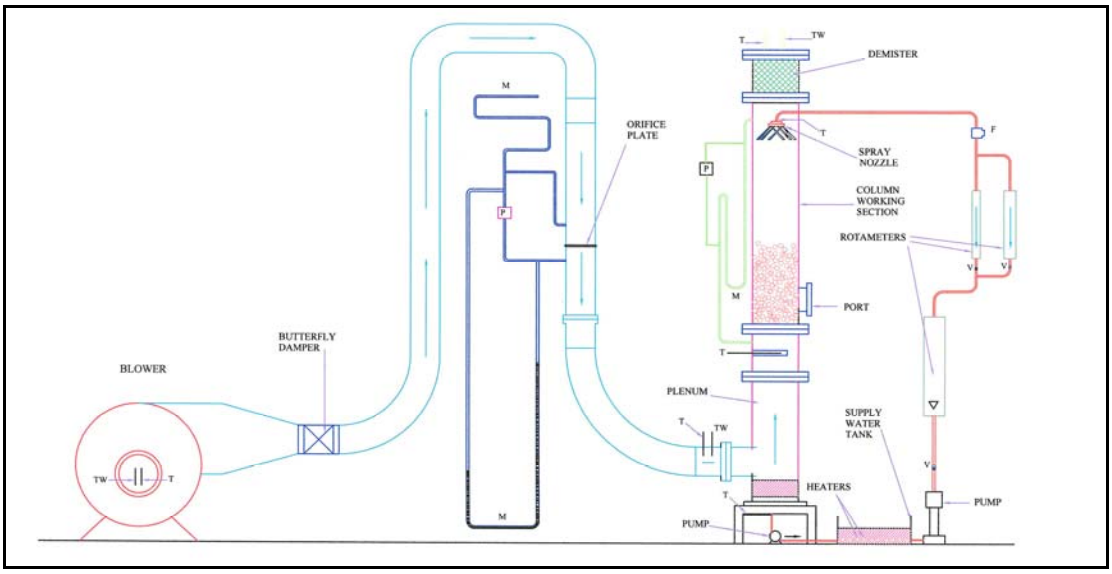

Figure 1 Schematic diagram of the FBCT apparatus

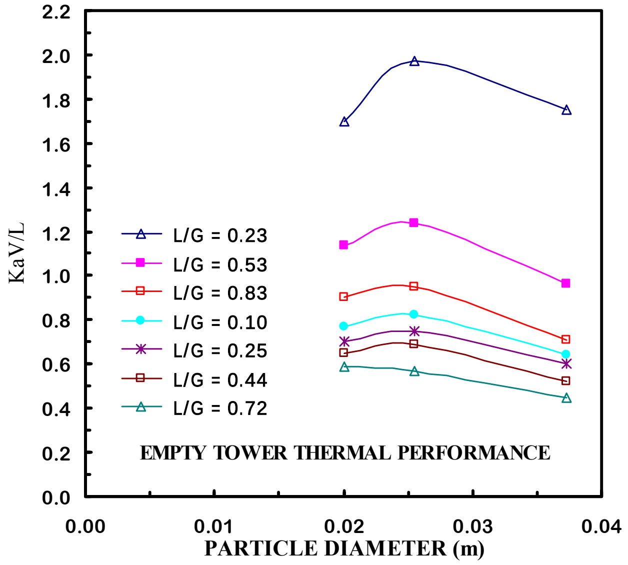

Figure 2 Effect of L/G and particle size on KaV/L (G=2.5 kg/s m^2 , V=300mm, H=600mm (coarse spray), $T_{w,i}$=42.0 ′C and T_{wb}=19.5 ′C).

3. Results and Discussion

The results showing the response of the FBCT performance characteristic to changes in different test variables are presented in Figures (2) to 4. In each figure, the caption shows the average values of other quantities that were held reasonably constant in the tests represented. Values of KaV/L were calculated from the test measurements using Merkel's equation (1):

$$KaV/L=dh/h_s-h_g \qquad (1)$$

where V is taken as the static bed height, h_w is the specific enthalpy of the water stream, h_s is the specific enthalpy of saturated air at the water temperature, hg is the specific enthalpy of the bulk air-water vapor mixture, given by $h_g = h_{g,,}+ (L/G)(h_w – h_a)$. The integral of equation (1) was evaluated using the 4-point Tchebycheff approximation given in BS4485 [6]. In Figure (2), KaV/L is plotted versus the particle diameter, dp, of the spherical packings for seven different values of L/G.

The air flow rate, static bed height, and the hot water inlet temperature are fixed. At all water/air mass flux ratios other than L/G=0.23, KaV/L is consistently lower for the 37.5 mm spheres than for the 20 mm spheres. Figure (2) also shows that, for all but the highest value of L/G, the value of KaV/L is higher for the 25.4 mm spheres. This at first may seem to suggest an optimum diameter for the spherical packings. It should be noted, however, that the particle densities of the three sizes of spheres do not vary monotonically with sphere diameter (According to Section 2). Therefore, it is unclear if the trends seen in Figure 2 are due to variation of the sphere diameter, the particle density or a combination of both. Further work, using lower density 25.4 mm diameter spheres, is to be carried out to clarify this matter.

A strong dependence of KaV/L on L/G is also evident in Figure (2), and it can easily be established that this is not a simple inverse relationship as suggested by the appearance of L in the denominator of KaV/L. Factoring KaV/L by L/G, noting that F and G are fixed, reveals that the more fundamental quantity Ka, the product of the mass transfer coefficient and the interfacial area per unit volume, increases with water mass flux as found by previous workers [7,8].

Figure (4) shows the effect of the air mass flux on KaV/L for a fixed water mass flux, and two different heights of the hot water spray nozzle. The packing used consisted of 37.5 mm diameter spheres and the static bed depth was 100 mm. As V and L are fixed, it can be deduced that the volumetric mass transfer coefficient, Ka, also increases with G in the same manner as KaV/L. Increasing the height of the spray nozzle above the packing introduces a spray zone that increases the interfacial area available for gas-liquid contact in the tower, and would be expected to lead to an increase in KaV/L for the tower. This is confirmed in Figure (4), where the lowest and highest air flow rates correspond to fixed bed operation, at a static bed height of 100mm, and full fluidization with an expanded bed height of approximately 400 mm respectively. Consequently with the nozzle set at H=400 mm the spray zone height reduces from 300 mm to zero as the bed expands, and for H=800 mm the corresponding reduction is from 700 mm to 400 mm. As the vertical separation of the two curves in Figure (4) remains reasonably constant, the percentage contribution to KaV/L of the additional spray zone height of 400 mm decreases as the bed expands with increasing gas flow.

It seems that a computer simulation program for the numerical prediction of the performance of a fluidized bed cooling tower confirms the finding of Gungor [9] who noted a similar tend using two spherical packing element diameters, 19.05 and 38.1 mm, approximating to the smallest and largest sizes used in this work.

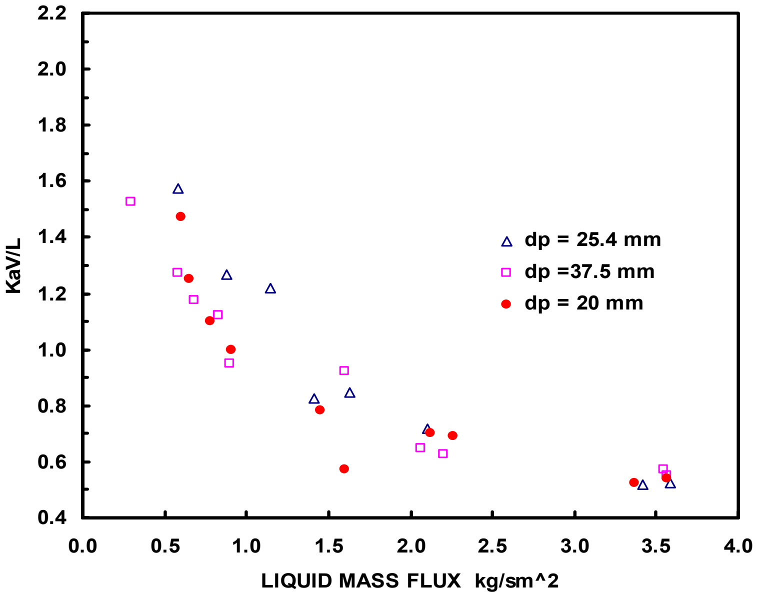

Figure 3 Effect of L and particle size on KaV/L (G=2.5 kg/s m^2 , V=300mm, H=400mm (fine spray), $T_{w,i}$=41.8 ′C and T_{wb}=17.2 ′C).

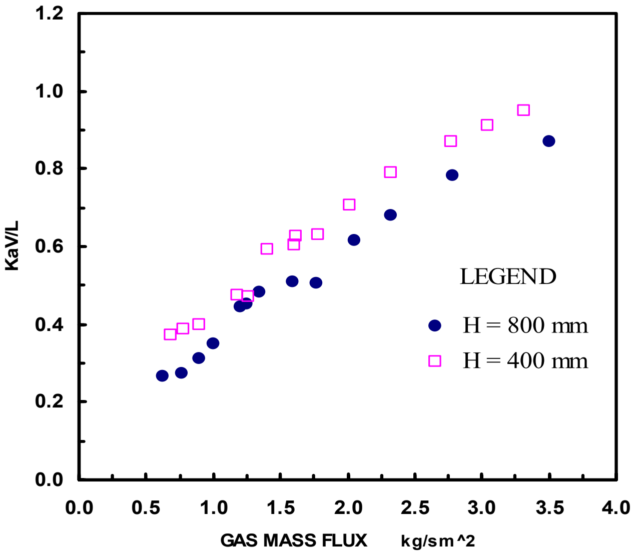

Figure 4 Effect of G and height of nozzle (fine spray) on KaV/L (L=3.63 kg/s m^2 , V=100mm, dp=37.5 mm, $T_{w,i}$=40.0 ′C and T_{wb}=20.3 ′C)

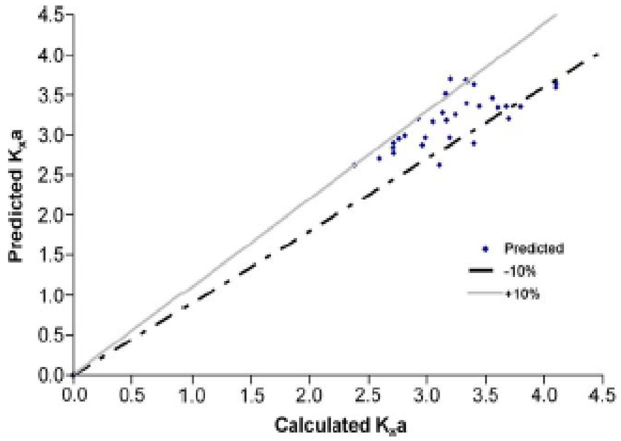

Figure 5 Relation between experimental and computer modeling for the volumetric mass transfer coefficient, Ka

4. Conclusions

This paper deals with thermal modeling of the fluidized bed and presents a mathematical mode and a computer simulation program for the numerical prediction of the performance of a FCT. The mathematical model is based on the heat and mass transfer equations; also experiments were conducted on a fluidized bed cooling tower and then the model is validated with the experimental data. Several field tests using different variables were performed for a fluidized bed cooling tower. The model and the experimental results presented below. Figure (5) shows the relation between experimental and computer modeling for the volumetric mass transfer coefficient, Ka.

The previous correlations found in the literature could not predict the volumetric mass transfer coefficient for the tested tower. A mass transfer coefficient correlation was developed and new variables were defined. This correlation can predict the mass transfer coefficient within a maximum of

It has been found that the accuracy of 5% obtained by using the chosen model can be then taken into account whenever this model is used to predict other characteristics related to the fluidized bed cooling tower.

5. References

1. H. R. Goshayeshi, “How to Design Compact Mass Transfer Packing For Maximum Efficiency,” Sixth international conference of heat transfer, New Forest, 2006.
2. W.J. M Douglas, “Heat and Mass Transfer in a Turbulent Bed Contactor,” Journal of heat and mass transfer, Vol. 40, No. 3, pp. 35-41, 2001.
3. R. G. Barile, “Performance and Design of a Turbulent Bed Cooling Tower,” AlChemE Symposium Series, Vol. 70, No. 138, pp. 154-162, 1974.
4. K. N Seetharamu, and S Swaroop, “The Effect of Size on the Performance of a Fluidized bed Cooling Tower,” Warme – und Stoffubertragung, Vol. 26, pp. 17–21, 1990.
5. H. El-Dessouky, “Thermal and Hydraulic Performance of a Three-Phase Fluidized Bed Cooling Tower,” Experimental Fluid and Thermal Science, Vol. 6, No. 4, 1993.
6. British Standard 4485, Water Cooling Towers, Part 2. Methods for Performance Testing, British Standards Institution, London, 2003.
7. S. Syahrul, “Thermal Analysis in Fluidized Bed Drying of Moist Particles,” Applied Thermal Engineering, Vol. 22, pp. 1763-1775, 2002
8. V. Manovic and M. Komatina, “Modeling the Temperature in Coal Char Particle During Fluidized Bed Combustion,” Fuel, Vol. 87, pp. 905-914, 2007.
9. A. Gungor, “Two Dimensional Coal Combustion Modeling of Fluidized Bed Cooling Tower,” International Journal of Thermal Science, Vol. 47, pp. 157-174, 2007.