INFLUENCE OF FILL TYPE AND FLOW ORIENTATION ON THE LEWIS NUMBER

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by

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As a follow-up to previous analysis of counterflow film and crossflow splash fill, the Lewis number is determined from experimental data for counterflow splash and crossflow film fill. The relative influence of fill type (film/splash) and flow orientation (counter/crossflow) on the Lewis number is examined in light of this more complete data set. A statistical comparison of these data indicates that the Lewis number is approximately 1.2 for all fills, irrespective of type or flow orientation.

INTRODUCTION

Many energy transfer processes can be classified as either heat or mass transfer. Some processes, such as evaporative cooling, involve these two transfer mechanisms simultaneously. The two components of evaporative cooling are typically referred to as sensible and latent heat transfer. The sensible component is that which due solely to a difference in temperature; whereas the latent is that which is due to a difference in concentration (in this case, of water vapor in air). The latent heat transfer is the product of the mass transfer and the energy which is associated with it.

Most engineering analyses assume some analog based on dimensionless parameters for one of the two components. Historically, analysis of cooling tower fills has been based on Merkel's application of just such an analog for the sensible heat transfer based on the evaporative mass transfer (Merkel 1926).

LeFevre (1985) has identified and quantified the various assumptions and simplifications in Merkel's analysis. One of the parameters identified is the ratio of the sensible to latent transfer coefficients. When expressed in dimensionless form, this ratio is called the Lewis number, as Lewis (1926) related this to a ratio of thermophysical properties. Merkel assumed that this parameter was equal to one.

The ratio of thermophysical properties for water evaporating into air under the conditions present in cooling towers varies between 0.8 and 0.9, so that assuming a value of one is not without basis. However, the transfer processes occurring in a cooling tower can be classified as turbulent and convective. There is ample experimental evidence to demonstrate that apparent properties such as viscosity and diffusivity in turbulent convection differ significantly from their molecular counterparts seen in laminar flow and pure conduction.

LeFevre has shown that Merkel's assumption of unity for the ratio of sensible and latent transfer coefficients is very convenient, but fortuitously not very critical to accuracy; because the latent transfer accounts for approximately 80 percent of the total. Others have reasoned that as long as one is consistent in applying and inferring fill performance, the uncertainty resulting from this assumption should be minimal. Nevertheless, it is rare to have experimental data for simultaneous sensible and latent heat transfer. Evaporative cooling is just such a process where the Lewis analogy can be tested. This test of the Lewis analogy should therefore be of interest to engineers concerned with heat and mass transfer processes which may be far removed from evaporative cooling.

LEWIS NUMBER FROM EXPERIMENTAL DATA

Because the sensible and latent heat transfer processes occur simultaneously in evaporative cooling, in order to determine both from experimental data it is necessary to solve for both simultaneously. Furthermore, it is necessary that they be physically distinguishable. If the processes are not physically distinguishable, then they cannot be analytically distinguishable. The minimum necessary condition is that the air be unsaturated throughout the exchange. Unsaturation is a necessary, though not sufficient, condition, as will be detailed subsequently. LeFevre and others have pointed out that Merkel's assumption of the ratio between sensible and latent heat transfer coefficients being equal to one becomes problematic for unsaturated cases, which are of particular concern with natural draft cooling towers.

In order to solve for both the sensible and latent heat transfer coefficients (two unknowns) simultaneously, there must be two distinct conditions (two independent equations) to be satisfied simultaneously. A logical choice would be matching the exit air humidity and enthalpy. The two independent, fundamental constraints are the conservation of mass for the water vapor and the conservation energy, respectively. The solution of this problem could be thought of as finding the combination of sensible and latent heat transfer coefficients which simultaneously satisfies both conditions. The mathematical means to this end may vary in effectiveness and efficiency; but the conceptual problem is the same.

While this may seem to be a straight-forward problem, such is not the case as there are two basic complications. First, even simultaneous linear equations can be ill-conditioned. Second, nonlinear problems may have no solutions or many solutions. The evaporative transfer process is nonlinear and any given data set may be ill-conditioned. Identifying profoundly ill-conditioned data, such as saturated or nearly saturated may be easy; but identifying mildly ill-conditioned data are not [recall that the air must be unsaturated in order to distinguish between the two processes]. Seemingly reasonable and consistent data sets can result in unreasonable and even multiple solutions (Benton, 1990). Residual maps have been introduced as a means of visualizing these anomalies (viz. unreasonable and multiple solutions). These maps show contours of equal residual, or error in satisfying the dual conditions of conservation of mass and energy.

In order to create a residual map it is first necessary to have a computer code which will calculate the exit air conditions given the inlet conditions and the two transfer coefficients. The FACTR computer code (Benton and Waldrop, 1988) was used for the present analysis. The residual maps are created by stepping through a range of values for the mass transfer coefficient and the sensible heat transfer coefficient and computing the exit air humidity and enthalpy. The difference between the measured and computed exit air humidity and enthalpy is the error. Dividing the difference in computed and measured exit air humidity by the difference in measured exit and inlet air humidity will normalize the error in the conservation of mass. The error in the conservation of energy can be similarly normalized by the measured energy transfer. The root-mean-square of these two errors is the residual. The root-mean-square was selected because a least-squares fit by definition minimizes the root-mean-square error. A point where the residual is zero would correspond to exact agreement with the data for the conservation of mass and energy.

These residual maps are constructed much like a standard topological map where longitude, latitude, and elevation (or X, Y, and Z) are analogous to mass transfer coefficient, sensible heat transfer coefficient, and residual (or normalized error), respectively. Hills would be analogous to large residuals or bad choices for transfer coefficients; whereas valleys would be analogous to small residuals or good choices for transfer coefficients. Ideally there should be only one valley surrounded by hills (i.e., only one clearly identifiable solution). Anomalies correspond to cases of more than one valley (i.e., more than one solution) or no valleys (i.e., no solutions). Several such anomalies have already been presented (Benton, 1990).

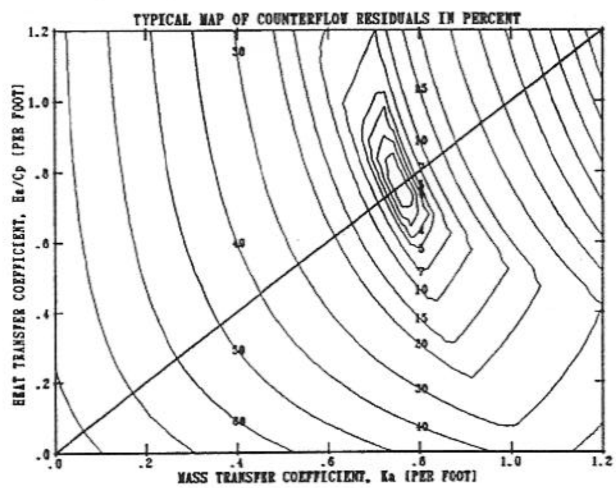

Figure 1. Typical Counterflow Residual Map

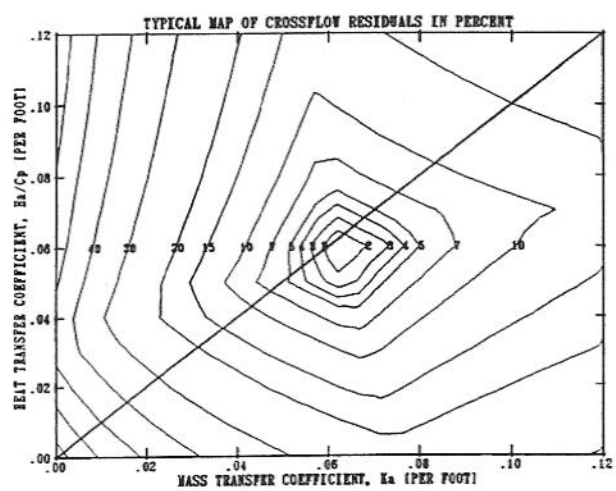

Figure 2. Typical Crossflow Residual Map

Figures 1 and 2 are typical residual maps for counterflow film and crossflow splash type fills respectively. The mass and sensible heat transfer coefficients form the X- and Y-axes respectively. The diagonal line indicates the loci of values where the Lewis number is equal to one. Along the diagonal line the mass transfer coefficient is equal to the sensible heat transfer coefficient divided by the specific heat, as suggested by Lewis. Dividing the sensible heat transfer coefficient by the specific heat gives it the same units as the mass transfer coefficient. Any point above the diagonal line would have a Lewis number greater than one and any point below the line would have a Lewis number less than one. The contours in Figures 1 and 2 form a "bull's-eye" whose center lies near the diagonal line.

Any point within the 5 percent contour represents a total error of 5 percent or less for both the conservation of mass and energy. If, for instance, the uncertainty in the measurements is on the order of 5 percent, then it can be argued that the mass and sensible heat transfer coefficients cannot be determined with any greater certainty than the region enclosed by the 5 percent contour line. Both of these maps represent well conditioned data sets and indicate a Lewis number of approximately one.

RESULTS AND DISCUSSION

The two basic fill types (film and splash) and two basic flow orientations (counter and cross) combine to make four combinations. Experimental data are shown for each in Figures 3 through 6 respectively. The mean Lewis number and 95 percent confidence interval are given in the lower right corner of each figure. The scatter is more pronounced for the crossflow than counterflow data. The majority of the data lie above the diagonal (i.e., Lewis number greater than 1) for all combinations except the crossflow splash.

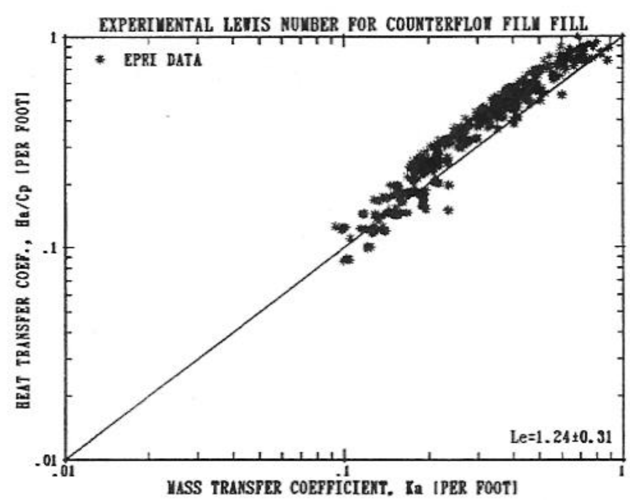

Figure 3. Experimental Lewis Number for Counterflow Film Fill

As previously indicated, profoundly ill-conditioned data are easily identified; however mildly ill-conditioned data are not. Data points were discarded if more than one solution was found (i.e., more than one set of closed contours or more than one valley for the topological analogy). Data points were also discarded if no solution could be found within 5 percent or if the error in the heat balance were more than 7.5 percent. It may be tempting to discard any data which deviate more than some arbitrary amount from a Lewis number of one; however, this would be "begging the question" at best.

The greater scatter seen in the crossflow data may result from a combination of ill-condition and the difficulty in measuring mean exit air conditions for crossflow fill. In general, more anomalies were found and more data points discarded from the crossflow sets than the counterflow. There were, of course, more cases of saturated exit conditions which were eliminated from the counterflow set than the crossflow, as these are not useful for determining experimental Lewis number.

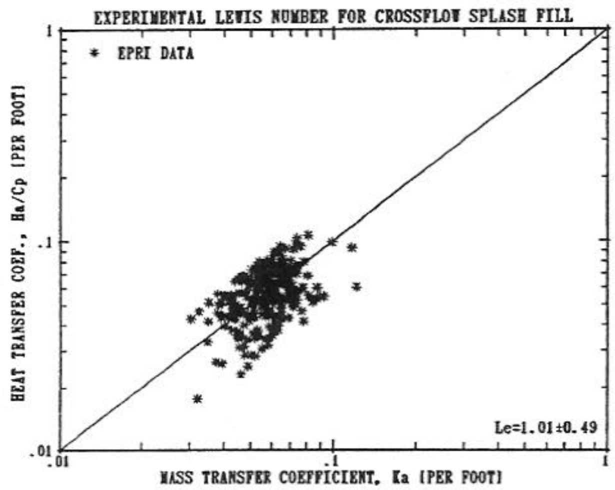

Figure 4. Experimental Lewis Number for Crossflow Splash Fill

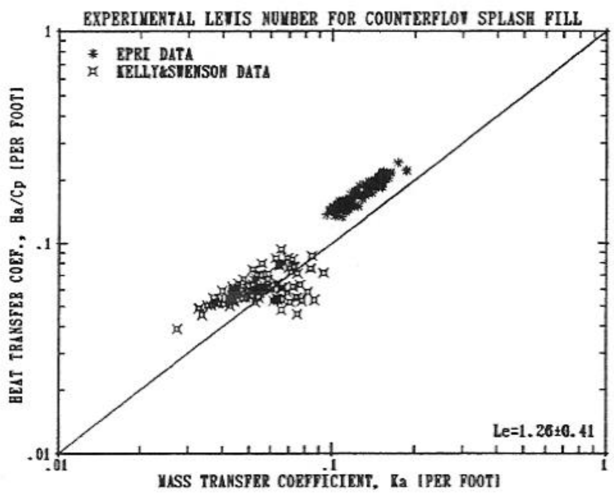

Figure 5. Experimental Lewis Number for Counterflow Splash Fill

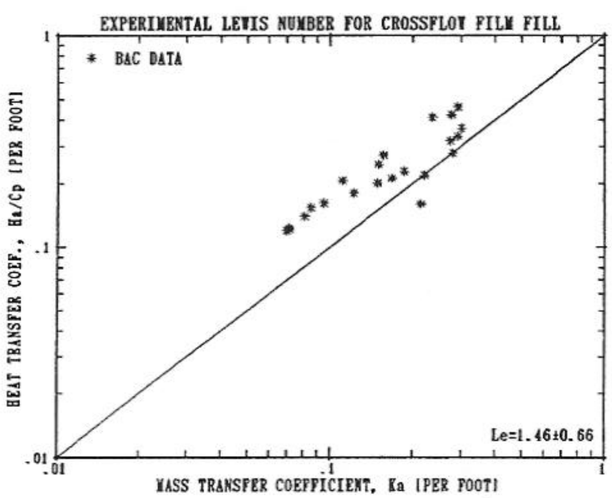

Figure 6. Experimental Lewis Number for Crossflow Film Fill

CONCLUSIONS

If the data for the four combinations of fill type and flow orientation are equally weighted and taken as a whole, the mean and 95 percent confidence interval for the Lewis number is 1.24±0.56. There is no statistical reason to conclude from these data that the Lewis number is other than 1.2 for all four combinations. This mean value is well within the 95 percent confidence interval for each set individually as well as all four together.

LeFevre (1985) has quantified the impact of Lewis number on performance calculations and shown it to be small compared to other factors such as neglecting evaporation or using 4-point Chebyshev integration. The difference between a Lewis number of 1 and 1.2 on performance calculations is minimal in most cases, and on the order of a few percent in selected extreme cases. Therefore, the pursuit of an experimental value for the Lewis number might be considered more academic than practical. While this may arguably be the case, it is still valuable to the better understanding of the combined mass and heat transfer process. Cooling tower fill data provides a rare opportunity to experimentally test the accuracy of the Lewis analogy.

ACKNOWLEDGMENTS

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