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MERCURY VAPOUR TRANSFER STUDIES: THE TRANSFER CHARACTERISTICS OF GAUZE SCREENS

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Abstract—The mercury evaporation technique has been used to determine the transfer characteristics of gauze screens. Data for four sizes of screen are reported.

The Schumann model of transient heat convection in a porous solid is shown to be inapplicable to matrices formed from gauze screens for the conditions under review here. Discrepancies between the present results and previous heat transfer investigations are explained in terms of the deficiencies of this model. The discrepancies are reduced by an analysis which includes the effect of longitudinal conduction in the screens.

NOMENCLATURE

A_F, superficial gauze screen area (ft^2);
A_S, solid area normal to conduction path (ft^2);
A_T, transfer area of one gauze screen (ft^2);
C, factor in equation (4) (—);
c_f, heat capacity of fluid ($Btu/lb_m degF$);
c_s, heat capacity of solid ($Btu/lb_m degF$);
D, diffusion coefficient (ft^2/h);
h, heat transfer coefficient ($Btu/ft^2 h degF$);
i, $\sqrt{-1}$ (—);
j_D, mass transfer j-factor, $\frac{\alpha k_c}{u} Sc^{2/3}$ (—);
j_H, heat transfer j-factor, $\frac{\alpha h}{\rho c_f u} Pr^{2/3}$ (—);
$J_o(\,)$, Bessel function of first kind and zero order (—);
k_c, mass transfer coefficient (ft/h);
k_f, thermal conductivity of fluid (Btu/ft h degF);
k_s, thermal conductivity of solid (Btu/ft h degF);
L, length of matrix (ft);
m, exponent in equation (4) (—);
$M_s(a)$, $\frac{d^s}{da^s}[J_o(2i\sqrt{a})]$ (—);
n, number of gauze screens in assembled matrix (—);
Pr, Prandtl number, $c_f \mu / k_f$ (—);
Re, Reynolds number, $4\rho u/\beta\mu$ (—);
Sc, Schmidt number, $\mu/\rho D$ (—);
t, time (h);
t_f, fluid temperature (°F);
t_{fo}, fluid temperature entering matrix (°F);
t_{fL}, fluid temperature leaving matrix (°F);
t_s, matrix temperature (°F);
t_{so}, initial matrix temperature (°F);
u, superficial fluid velocity (ft/h);
w_f, fluid mass flow rate (lb_m/h);
w_s, total mass of matrix (lb_m);
x, longitudinal co-ordinate ($x = 0$ at matrix entrance) (ft);
y, dimensionless longitudinal co-ordinate, x/L (—);
Z, number of transfer units $\frac{hnA_T}{w_f c_f}$ (—).

Greek symbols

α, porosity of a single gauze screen (—);
β, heat transfer area per unit volume for a single gauze screen (ft^{-1});
θ_f, dimensionless fluid temperature, $\frac{t_f - t_{so}}{t_{fo} - t_{so}}$ (—);

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θ_f^*, dimensionless temperature of fluid leaving matrix, $\frac{t_{fL} - t_{so}}{t_{fo} - t_{so}}$ (—);

θ_s, dimensionless matrix temperature, $\frac{t_s - t_{so}}{t_{fo} - t_{so}}$ (—);

λ, conduction parameter, $\frac{k_s A_s}{w_f c_f L}$ (—);

μ, viscosity (lb_m/fth);

ρ, fluid density (lb_m/ft^3);

τ, dimensionless time, $\frac{hnA_T t}{W_s c_s}$ (—).

Superscript

$^\circ$, denotes value of parameter determined by assuming $\lambda = 0$.

INTRODUCTION

A COMPACT regenerative heat exchanger requires a core matrix with a suitably large heat transfer area to bulk volume ratio. From Table 1 it may be seen that this ratio (β) is favourable for wire gauze screens and such screens may therefore form suitable cores for regenerative heat exchangers. Convective heat transfer coefficients will then be required for design purposes.

In addition, such data may be useful in the design of chemical reactors since, as Oele [1] has suggested, the rate determining step in fast catalytic reactions may be the transport of reactant molecules to the catalyst surface. The oxidation of ammonia by air is such a reaction and the platinum/rhodium catalyst is usually in the form of a fine flat gauze. Convective mass transfer coefficients for gauzes would therefore be useful design information. These coefficients could be obtained from corresponding heat transfer data by use of the analogy between heat and mass transfer, i.e. by assuming $j_D = j_H$.

The heat transfer characteristics of gauze screens have been investigated by Coppage and London [2]. Six sizes of stainless steel gauze were studied, the assembled matrices consisting of between three and sixty-five gauzes. The experimental method consisted of heating the matrix (initially at a uniform temperature) by means of a stream of air which entered at a constant higher temperature. The temperature–time response of the fluid leaving the matrix was recorded. This response was then compared with that predicted by the Schumann analysis [3] and the heat transfer coefficient deduced. The method of comparison was developed by Locke [4] and involved determining the maximum slope of the response curve. Some of the results of Coppage and London for four sizes of gauze similar to those used in the present work are shown in Figs. 1–4.

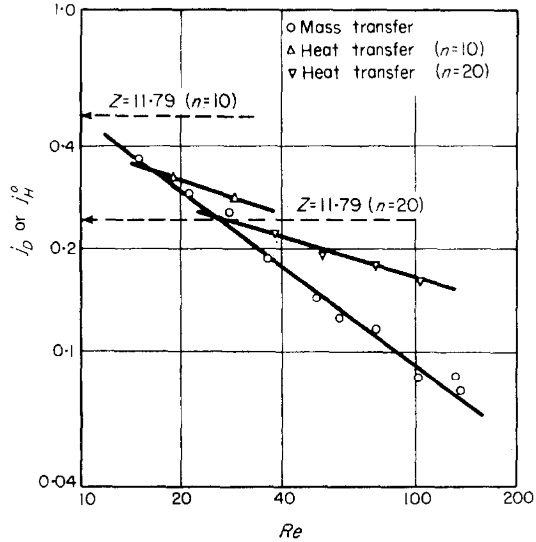

FIG. 1. Heat and mass transfer results for 10 mesh gauze.

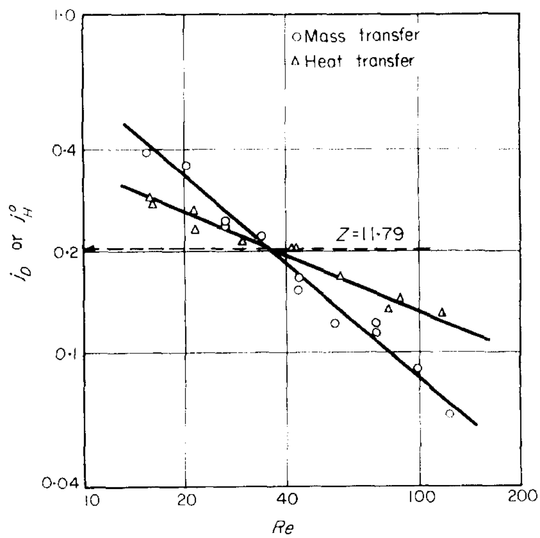

FIG. 2. Heat and mass transfer results for 16 mesh gauze.

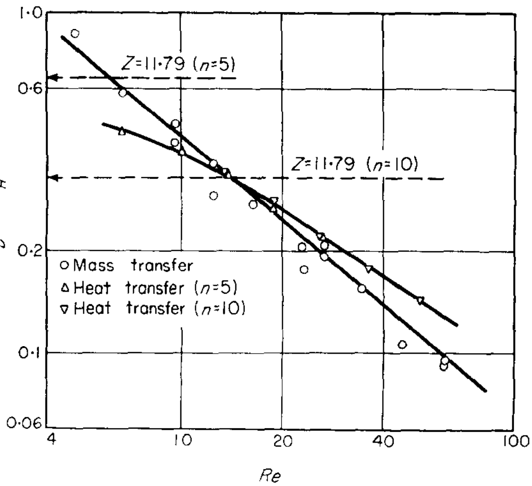

FIG. 3. Heat and mass transfer results for 24 mesh gauze.

The theory of Schumann involves a number of idealisations, the most restrictive being that no thermal conduction takes place in the matrix in a longitudinal direction [5]. Under these conditions, and neglecting heat storage in the fluid held in the matrix, the relevant differential equations are:

$$\left.\begin{aligned} &\frac{\partial \theta_s}{\partial \tau} = \theta_f - \theta_s \\ &\frac{\partial \theta_f}{\partial y} = Z(\theta_s - \theta_f) \\ &\text{with the conditions} \\ &\theta_s = 0 \text{ at } \tau = 0 \text{ for all } y \\ &\theta_f = 1 \text{ at } y = 0 \text{ for all } \tau. \end{aligned}\right\} \quad (1)$$

The solutions to (1) are given by Schumann and, in particular, the temperature of the fluid leaving the matrix is

$$\theta_f^* = 1 - \exp(-Z - \tau) \sum_{s=1}^{\infty} Z^s M_s(Z\tau). \quad (2)$$

Numerical values of θ_f and θ_s for a range of values of Zy and τ are given by Jakob [6].

Allowing for the effect of longitudinal conduction in the matrix the differential equations become:

$$\left.\begin{aligned} &\frac{\partial \theta_s}{\partial \tau} = \theta_f - \theta_s + \frac{\lambda}{Z} \frac{\partial^2 \theta_s}{\partial y^2}, \\ &\frac{\partial \theta_f}{\partial y} = Z(\theta_s - \theta_f) \\ &\text{with the same conditions as (1).} \end{aligned}\right\} \quad (3)$$

Creswick [7] has obtained finite difference solutions to these equations and Mondt [5] has extended these solutions to show the effect of longitudinal conduction upon the maximum slope of the response curve over a range of values of Z. Mondt has also demonstrated the presence of longitudinal conduction in a particular matrix geometry and has shown that the solution to (3) describes quantitatively the effects observed.

In addition to the effect of longitudinal conduction in the matrix, Green and Perry [8] have considered the influence of the longitudinal diffusion of heat in the fluid upon the response curve.

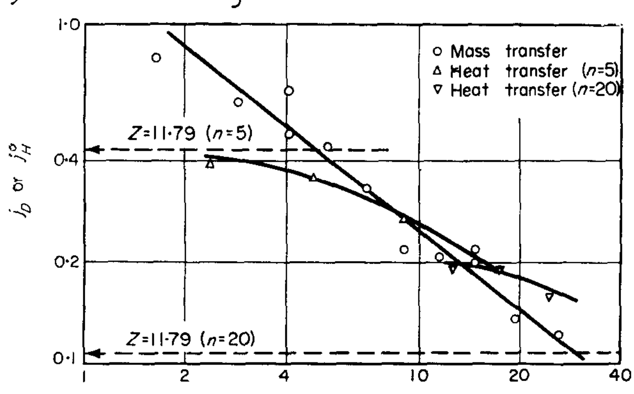

FIG. 4. Heat and mass transfer results for 60 mesh gauze.

The alternative approach is to determine the mass transfer characteristics of gauze screens and to use these data to predict reactor performance and heat transfer behaviour. The purpose of the work on which this paper is based was to obtain such information using the mercury evaporation technique [9, 10].

EXPERIMENTAL

The copper gauze screens used in the present work were identical in nominal mesh size and wire gauge number to four of the six sizes of screen investigated by Coppage and London. Nevertheless measurement of the screen dimensions revealed differences in the parameters porosity (α) and specific surface area (β). These discrepancies (Table 1) are probably due to the difficulty of obtaining accurate measurements of the screen dimensions (particularly screen thickness). Differences between American and British practices in wire screen weaving and the use of different wire materials may also partly account for the discrepancies.

Table 1. Gauze screen dimensions

Nominal gauze dimensions		Present work		Coppage and London [2]	
mesh	wire diameter (in)	α	β (ft^{-1})	α	β (ft^{-1})
10	0·025	0·817	390	0·817	352
16	0·018	0·795	535	0·766	624
24	0·014	0·763	858	0·725	980
60	0·0075	0·690	2030	0·675	2090

The transfer data discussed below will be presented in terms of the appropriate set of values of α and β.

The mass transfer coefficients were determined using the mercury evaporation technique introduced by Maxwell and Storrow [9]. The technique has since been used by Potter [11], Haggart [12] and Williams [13] as well as in the present work. The essential principle of the technique is, as described by Maxwell and Storrow, the measurement of the rate of evaporation of a thin film of mercury from a surface into a flowing gas stream. The advantages of the technique include the availability of a sensitive concentration measuring device in the form of an ultra-violet absorptiometer and the possibility of fabricating robust models of complicated shape from the base metal (e.g. copper). Details of the method including improvements introduced by Williams are described elsewhere [9, 10, 13].

In the present work a circular piece of mercurized gauze 4 inches in diameter was located in a perspex holding ring at the downstream end of a glass calming section (27 in long $\times$ 4 in diameter). An unmercurized 16 mesh gauze placed 1 in upstream of the test gauze served as a flow smoothing screen. The experimental section was fitted with inlet and outlet sampling points connected to the ultra-violet absorptiometer and a nichrome V/advance thermocouple was located immediately before the smoothing gauze.

All experimental runs were carried out using only a single piece of mercurized gauze, in contrast with the work of Coppage in which a matrix of between three and sixty-five gauzes was used. Mass transfer coefficients were calculated from the gas (nitrogen) flow rate and temperature, the gauze dimensions, and the inlet and exit mercury vapour concentration, using the logarithmic-mean concentration difference (i.e. assuming piston flow). The coefficients thus calculated should be comparable with those found by Coppage and London since piston flow is an implicit assumption in the Schumann theory.

The results are presented in Figs. 1–4 as plots of j-factor vs. Reynolds number. This presentation corresponds to that adopted by Coppage and London except that these authors used a dimensionless heat transfer group equal to $j_H Pr^{1/3}$ rather than the more usual j-factor used here. Following the practice of Coppage and London the results may be expressed in the form

$$j_D = C(Re)^{-m}. \tag{4}$$

Values of the factor C and the exponent m are given in Table 2.

Results obtained by Coppage and London for similar gauzes in the same range of Reynolds number are also given in Figs. 1–4.

Table 2. Factors and exponents in equation (4)

Gauze mesh	C	m
10	2·62	0·73
16	4·26	0·85
24	2·80	0·81
60	1·46	0·77

DISCUSSION

It is clear from Figs. 1–4 that there is very little agreement between the present mass transfer data and the corresponding heat transfer results of Coppage and London. The discrepancies are too large to be explicable in terms of the differences in gauze dimensions which may exist between the two investigations. Nor can they be removed by the use of one rather than two sets of values for α and β since these parameters determine the constant C but probably not the exponent m in equation (4).

It is suggested that longitudinal conduction in the matrix is a more likely explanation of the discrepancies. Examination of the paper by Mondt [5] indicates that if the conduction parameter (λ) is not zero then the following relationships exist between the apparent and actual values of Z:

$$Z^\circ > Z \quad \text{for} \quad Z < 11{\cdot}79$$

$$Z^\circ = Z \quad \text{for} \quad Z = 11{\cdot}79$$

$$Z^\circ < Z \quad \text{for} \quad Z > 11{\cdot}79$$

where the superscript $^\circ$ denotes the apparent value of the parameter, i.e. the value calculated assuming $\lambda = 0$.

Now, if the heat transfer coefficient is independent of the number of gauzes, Z is related to j_H by the expression

$$Z = j_H \frac{nA_T}{\alpha A_F} Pr^{-2/3}. \qquad (5)$$

So that, if $\lambda \neq 0$ and j_H° and j_D ($=j_H$) are plotted against Reynolds number, (i) for fixed n and a given type of gauze, the latter curve will be steeper than the former and the two will intersect at a value of j_H equivalent to $Z = 11{\cdot}79$, and (ii) for different numbers of the same type of gauze different j_H° curves will be obtained, since equation (5) shows that this corresponds to different values of Z.

The results presented in Figs. 1–4 may be analysed in terms of these predictions. Examination of Fig. 1 shows that the heat transfer results for $n = 20$ are in good agreement with prediction (i) above. For $n = 10$ the two lines intersect at a value of $Z < 11{\cdot}79$ but only two heat transfer points are available in this case. The distinction between $n = 10$ and $n = 20$ seems clear, in accordance with prediction (ii). Coppage and London report results for $n = 20$ only in the case of 16 mesh gauze. These data (Fig. 2) exhibit exactly the behaviour predicted under (i) above. For the 24 mesh gauze (Fig. 3) the data for $n = 10$ follow prediction (i) but the heat transfer results for $n = 5$ intersect the mass transfer line at a value of Z less than 11·79. Contrary to prediction (ii) the data for $n = 5$ and $n = 10$ are not distinguishable. The predictions are supported by the results for the 60 mesh gauze (Fig. 4) in that the data for $n = 5$ and $n = 20$ are distinguishable and the j_H° curves have smaller slopes than the j_D line. However the points of intersection are well below $Z = 11{\cdot}79$ for $n = 5$ and well above $z = 11{\cdot}79$ for $n = 20$.

In general the discrepancies between the heat and mass transfer results for similar gauzes are consistent with the former being influenced by longitudinal conduction in the matrix.

The effect of longitudinal conduction upon heat transfer may also be examined by predicting the response curves for the matrices of Coppage and London. Three bases of prediction were used by the present authors: (a) $\lambda = 0$ and the value of Z reported by Coppage and London, (b) $\lambda = 0$ and the value of Z found by analogy from j_D, and (c) an estimated λ and the value of Z used in (b).

Cases (a) and (b) were calculated using the Schumann solution (2). Case (c) was calculated using a modified version of Creswick's finite difference solution of (3). Data for the calculation of the conduction parameter for case (c) are given by Coppage and London except for the area of solid normal to the conduction path (A_S). In the present work this was estimated as

$(1 - \alpha)A_F$ by analogy with the flow area αA_F. This estimate also appears to have been used by Green and Perry [8]. All calculations were carried out on a Ferranti Mercury digital computer.

Typical predictions are compared with the experimental response curves determined by Coppage in Figs. 5–12. The dimensionless temperature response θ_f^* is plotted against the dimensionless time τ/Z and the letters 'A', 'B' and 'C' denote the predicted curves for cases (a), (b) and (c) above. It is apparent from Figs. 5–12 that the values of Z reported by Coppage and London are not consistent with the experimental results upon which they are based. It is also clear that there is little (if any) improvement in the predicted curves if values of Z from

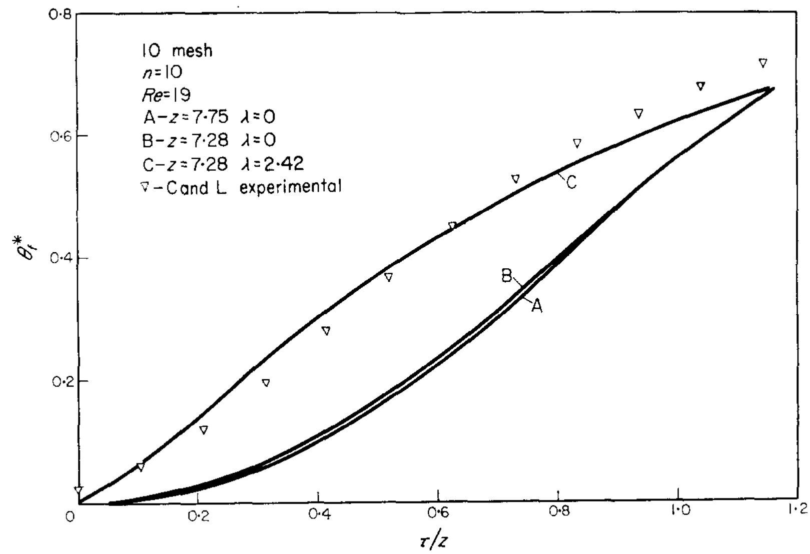

FIG. 5. Predicted and experimental response curves for 10 mesh gauze for $n = 10$ and $Re = 19$.

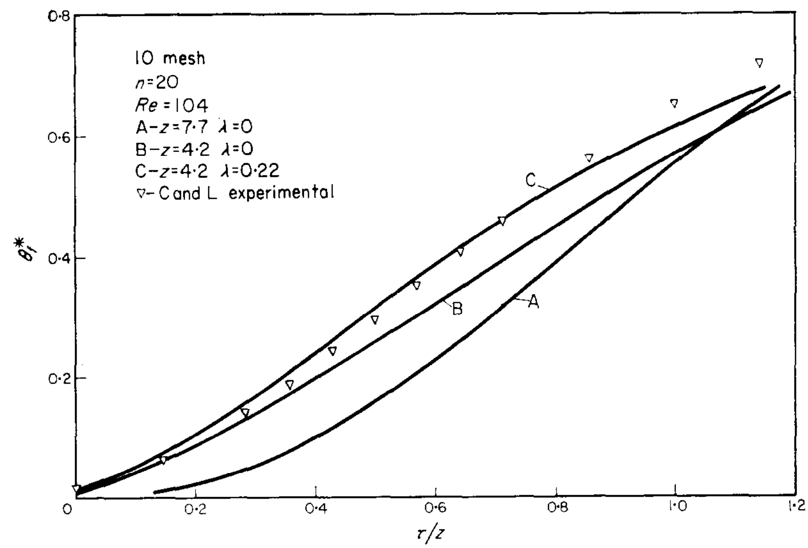

FIG. 6. Predicted and experimental response curves for 10 mesh gauze for $n = 20$ and $Re = 104$.

the present work are used with the Schumann theory. The predictions based on mass transfer data with allowance for longitudinal conduction are the most satisfactory although the discrepancy between experiment and prediction is still large in some cases. The values of λ used in the predictions are, of course, only estimates, it being difficult to assign a definite value to A_S and, to a lesser extent, to L. The values of L used are those reported by Coppage and London

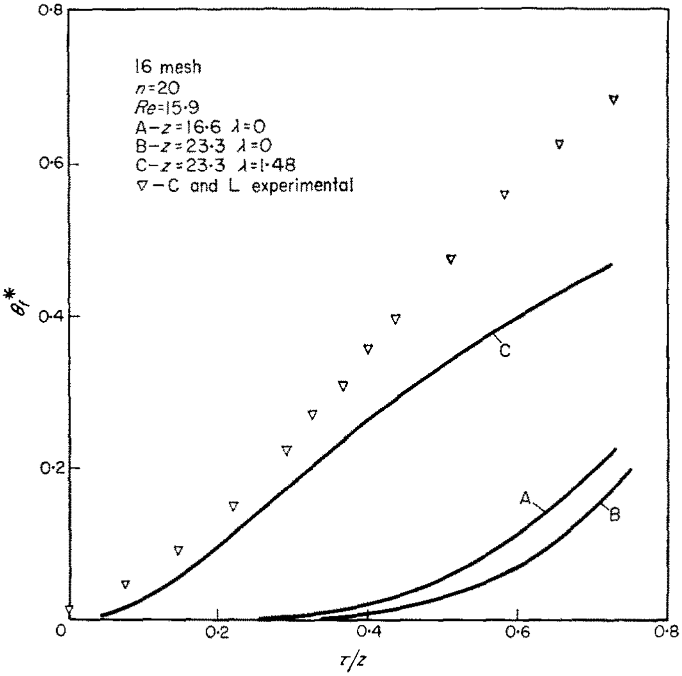

FIG. 7. Predicted and experimental response curves for 16 mesh gauze for $n = 20$ and $Re = 15{\cdot}9$.

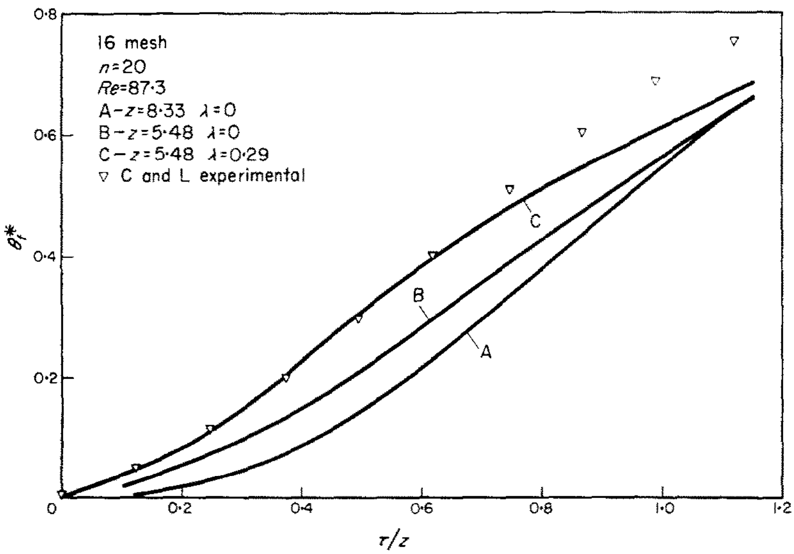

FIG. 8. Predicted and experimental response curves for 16 mesh gauze for $n = 20$ and $Re = 87{\cdot}3$.

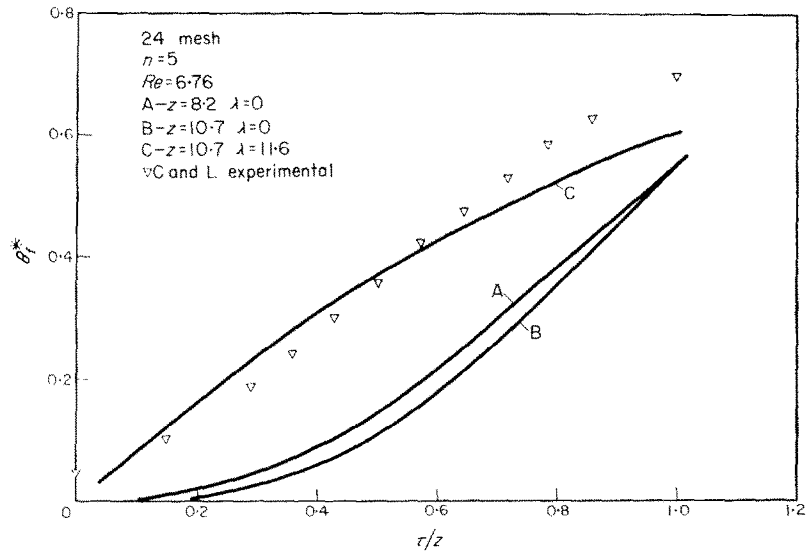

FIG. 9. Predicted and experimental response curves for 24 mesh gauze for $n = 5$ and $Re = 6{\cdot}76$.

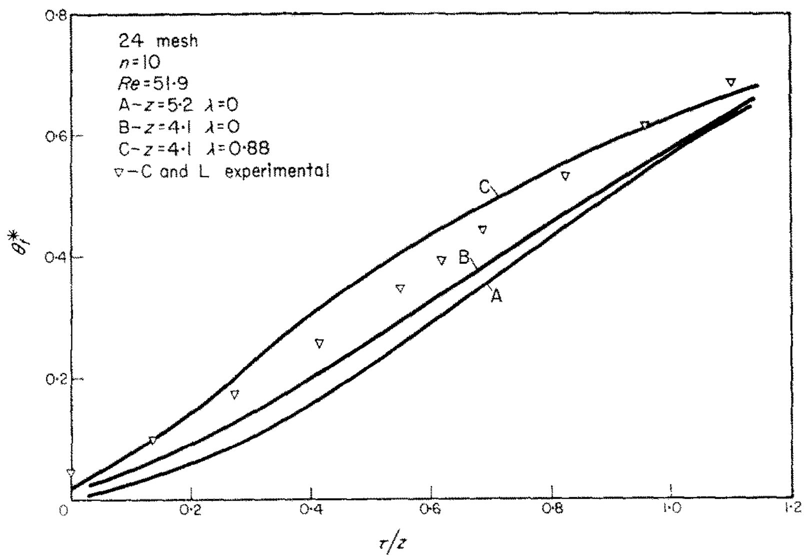

FIG. 10. Predicted and experimental response curves for 24 mesh gauze for $n = 10$ and $Re = 51{\cdot}9$.

and the estimate of A_S as $(1 - \alpha)A_F$ appears to have been reasonably successful.

It is interesting to note that the response curves are not very sensitive to changes in Z. This fact provides some justification for using mass transfer data obtained for the present gauzes to predict the heat transfer behaviour of gauzes of somewhat different α and β. Conversely, the response curves are sensitive to the influence of longitudinal conduction in the solid and this effect should be allowed for in experiments on transient heat convection in packed beds and similar equipment.

The model of piston flow with axial conduction in the matrix (due to Creswick) thus appears to be superior to that of Schumann for the gauze

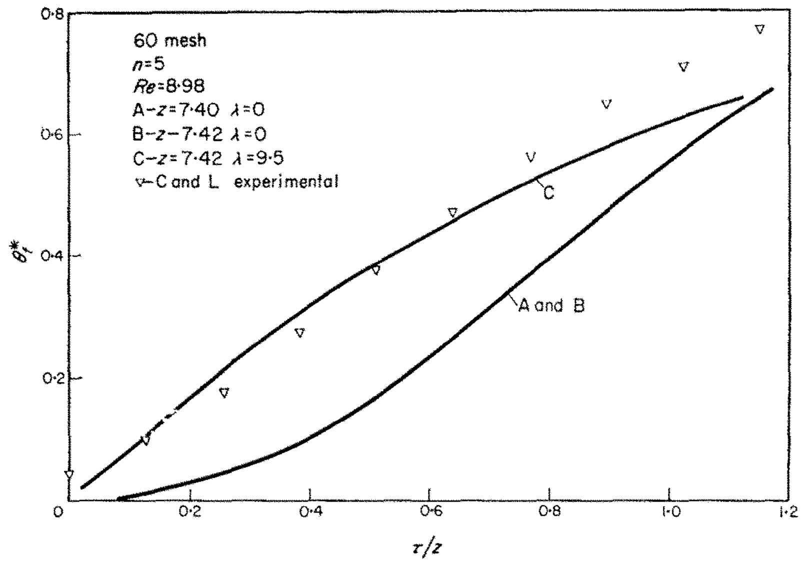

FIG. 11. Predicted and experimental response curves for 60 mesh gauze for $n = 5$ and $Re = 8{\cdot}98$.

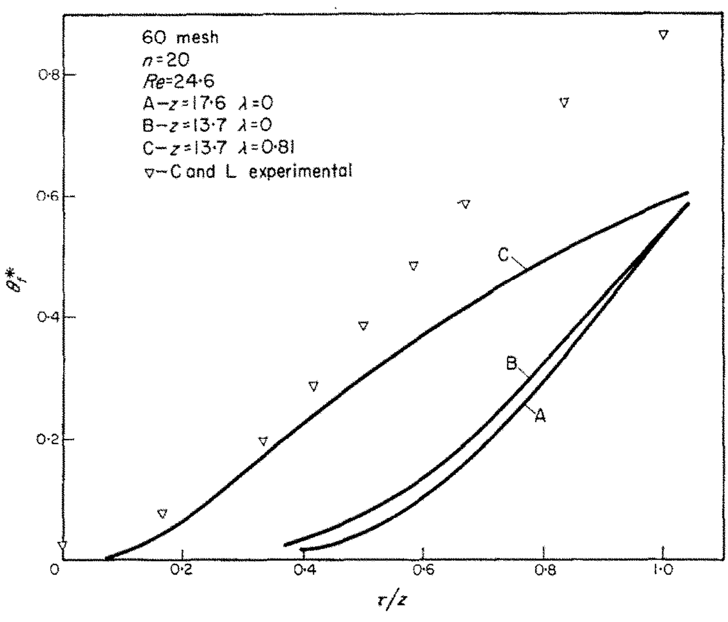

FIG. 12. Predicted and experimental response curves for 60 mesh gauze for $n = 20$ and $Re = 24{\cdot}6$.

systems studied by Coppage and London. Figs. 5–12 show, however, that the model is not entirely satisfactory. In particular, the theory fails to predict the rapid rise of θ_f^* which was usually observed at high values of τ/Z. The most likely explanation (which is supported by the recent analysis of Green and Perry [8]), is that the assumption of zero longitudinal diffusion of heat in the fluid is not valid. Information, such as effective longitudinal thermal diffusivity, which is not at present available would be required to elucidate this point.

CONCLUSIONS

1. Mass transfer data have been obtained for four sizes of woven wire screen and are reported in dimensionless form.

2. These data may be useful in the design of catalytic reactors using woven wire catalyst elements and for obtaining, by analogy, the corresponding heat transfer characteristics.

3. The discrepancies between the present results and previously determined heat transfer data are shown to be consistent with the latter being affected by heat conduction in the gauze matrix.

4. The model of piston flow with axial conduction in the matrix (due to Creswick) is shown to be superior to that of Schumann for heat transfer in gauze matrices.

5. Further work is required to establish whether axial diffusion of heat in the fluid phase is an important factor in heat transfer in gauze matrices.

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Résumé—On a utilisé la technique d'évaporation du mercure pour déterminer les caractéristiques de transmission de grilles. Les données numériques relatives à 4 dimensions de mailles sont présentées.

Dans les conditions considérées ici, on démontre quele modèle de Schuman pour la convection de la chaleur en régime transitoire dans un solide poreux ne peut pas s'appliquer à des ensembles de grilles. Les écarts entre les résultats actuels et les recherches antérieures sur la transmission de chaleur s'expliquent par les insuffisances de ce modèle. Les écarts se réduisent si l'on tient compte de l'effet de conduction longitudinale dans les écrans.

Zusammenfassung—Die Quecksilberverdampfungstechnik diente zur Bestimmung der Übergangscharakteristika bei Gewebegittern. Die Daten von vier Gittergrössen werden angegeben. Das Schumann-Modell für instationären Wärmetransport in porösen Festkörpern erweist sich für Einbauten aus Gewebegittern unter vorliegenden Versuchshedingungen nicht anwendbar. Abweichungen zwischen erzielten Ergebnissen und früheren Wärmeübergangsuntersuchungen lassen sich als Modellunzulänglichkeiten erklären. Eine Analyse, die den Einfluss der Längsleitung in Gittern berücksichtigt, führt zur Verminderung der Diskrepanzen.

Аннотация—Использован метод испарения ртути для определения тепло-и массообменных характеристик проволочных экранов. Приведены данные для экранов четырех размеров. Показано, что для рассматриваемых в настоящей задаче условий модель

Шумана неустановившегося режима конвекции тепла в пористом твердом теле неприемлема для матриц из проволочных экранов. Расхождения между настоящими результатами и результатами предыдущих исследований по теплообмену объясняются неточностями данной модели. Эти расхождения уменьшаются при учете влияния продольной проводимости экранов.