Int. J. Heat Mass Transfer. Vol. 27, No. 7, pp. 971 978. 1984
Printed in Great Britain

0017-9310/84 $3.00 + 0.00

A MODIFIED SELECTED POINT MATCHING TECHNIQUE FOR TESTING COMPACT HEAT EXCHANGER SURFACES

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(*Received* 17 *March* 1983 *and in revised form* 20 *July* 1983)

Abstract—A transient technique taking care of the longitudinal heat conduction effect is developed in which an experimentally determined $T^*_{f1}(\theta^*)$ is used as the inlet fluid temperature condition. It is shown that the longitudinal conduction effect must be included for both $N_{tu} \geqslant 3$ and $\lambda_1 N_{tu} \geqslant 0.06$ and there exists an optimum matching time interval. An empirical formula for correcting the heat conduction effect for $N_{tu} \leqslant 20$, the optimum matching time interval and an uncertainty analysis are included. The validity of this technique is confirmed by the good agreement between the test data and the theoretically predicated results.

NOMENCLATURE

A	total heat transfer area of test core
A_s	solid plate cross-sectional area available for heat conduction in flow direction
A_c	minimum free flow area of test core
A_{fr}	total frontal area of test core
C_f	specific heat of fluid at constant pressure
C_s	specific heat of solid material
D_h	hydraulic diameter of flow channel
h_m	mean heat transfer coefficient
L	total flow length of test core
$\dot{m}_f$	mass flow rate of fluid
M_s	solid material mass of test core
T_f	fluid temperature
T_{fm}	maximum stable fluid temperature
T_i	initial fluid and solid material temperature
T_s	solid material temperature
V_{fr}	frontal free flow velocity
x	length coordinate.

Greek symbols

λ_s	thermal conductivity of solid material
θ	time
τ_i	time constant of inlet fluid temperature.

Dimensionless groups

N_{tu}	number of heat transfer units, $h_m A/\dot{m}_f C_f$
T^*_f	dimensionless fluid temperature, $(T_f - T_i)/(T_{fm} - T_i)$
T^*_s	dimensionless solid material temperature, $(T_s - T_i)/(T_{fm} - T_i)$
x^*	dimensionless length variable, x/L
θ^*	dimensionless time, $\dot{m}_f C_f \theta/M_s C_s$
λ_l	longitudinal heat conduction parameter of solid material, $\lambda_s A_s/\dot{m}_f C_f L$
τ^*	dimensionless time constant, $\dot{m}_f C_f \tau_i/M_s C_s$.

INTRODUCTION

THE HEAT transfer performance of compact heat exchanger surfaces is usually determined by the steady-state method described in ref. [1], but it can only be applied to the range $0.2 \leqslant N_{tu} \leqslant 3$ [1]. The transient method has certain advantages over the steady-state method [2, 3]. Therefore, attention has recently been attracted to the transient method.

The transient technique consists of subjecting a sample of the heat transfer surface to a sudden change in temperature of the transfusing fluid and measuring the response, $T^*_{f2}(\theta^*)$, of the fluid leaving the test core. The heat transfer performance is then determined by matching the measured outlet fluid temperature response, $T^*_{f2,exp}(\theta^*)$, with a similar theoretical solution from the mathematical model used. Consequently, for accurate test results, it is necessary to use an appropriate mathematical model as the basis for the technique and to reduce measuring uncertainties as far as possible. As a matter of fact, it is impossible to eliminate these uncertainties completely, therefore an appropriate matching technique must be sought to minimize the effects of these uncertainties.

In Schumann's model used in the early single-blow transient technique [4, 5], the effect of longitudinal conduction was neglected and a step change of inlet fluid temperature was assumed [6]. In the matching techniques the maximum-slope technique proposed by Locke [2] and extended by Howard, who included the effect of longitudinal conduction by the finite-difference method [7], is widely used at present. But it is only applicable to $N_{tu} > 3.5$ [8]. As the assumption of step change was made in their analyses, it might lead to a considerable inaccuracy in N_{tu} for such test cases where a step change could not be produced. In view of this, Liang and Yang used the experimentally determined response of inlet fluid temperature in their analysis neglecting longitudinal conduction, and proposed a technique to match the measured values of the outlet fluid temperature, selected at different times on the response curve, with their analytical solution [9]. This technique (hereafter referred to as the 'selected point matching technique') can not only enlarge the N_{tu} test range, but also avoid the errors resulting from the deviation of the actual inlet fluid temperature from the step change. However, the effect of longitudinal conduction was neglected, and how to select the matching point to minimize the effects of temperature measurement uncertainty were not analysed in ref. [9]. It will be shown that the accuracy of the test results obtained by this technique depends distinctly on whether a suitable matching point is selected or not.

The main purpose of this paper is to extend Liang and Yang's analysis to include the effect of longitudinal conduction by the finite-difference method and to study the effect of the matching time selected on test results for an uncertainty in temperature measurement. As a result, the optimum matching time intervals which minimize the effect of measuring uncertainty of temperature on test results will be obtained.

GOVERNING EQUATIONS AND METHOD OF SOLUTION

Assumptions made in the following analysis are:

(1) fluid flow is uniform and steady;

(2) properties of both fluid and solid surfaces are constant;

(3) thermal conductivities of both fluid and solid surfaces are infinite perpendicular to the flow direction;

(4) heat conduction of fluid is negligible in the fluid flow direction;

(5) fluid thermal capacitance is neglected relative to the capacitance of solid surfaces;

(6) solid surfaces are homogeneous;

(7) the boundaries of the test core are adiabatic.

The transient heat transfer phenomenon including the effect of longitudinal conduction of surfaces can thence be described by the following equations

$$\frac{\partial T_f^*}{\partial x^*} = N_{tu}(T_s^* - T_f^*), \tag{1}$$

$$\frac{\partial T_s^*}{\partial \theta^*} - \lambda_1 \frac{\partial^2 T_s^*}{\partial x^{*2}} = N_{tu}(T_f^* - T_s^*), \tag{2}$$

with the initial and boundary conditions as

$$T_s^*(0, x^*) = 0, \tag{3}$$

$$\left(\frac{\partial T_s^*}{\partial x^*}\right)_{x^*=0} = \left(\frac{\partial T_s^*}{\partial x^*}\right)_{x^*=1} = 0, \tag{4}$$

$$T_f^*(\theta^*, 0) = T_{f1}^*(\theta^*). \tag{5a}$$

It has been justified on our test rig that the actual inlet fluid temperature change, $T_{f1}^*(\theta^*)$, can be closely fitted with an exponential function proposed in ref. [9]. Thus

$$T_{f1}^*(\theta^*, 0) = 1 - \exp(-\theta^*/\tau^*), \tag{5b}$$

where $\tau^* = \dot{m}_f C_f \tau_i / M_s C_s$ is the dimensionless time constant in which τ_i is the time constant of the measured inlet fluid temperature. For our heating system, it was accurately described by $\tau_i = 2.16 V_{fr}^{-0.74}$ through experimental measurements.

Numerical solutions to the above problem were obtained using a finite-difference method. The network was constructed as

$$x^* = (j - \tfrac{1}{2})\Delta x^*, \quad j = 0, 1, 2, \ldots, m+1, \quad \Delta x^* = 1/m,$$

$$\theta^* = n\Delta\theta^*, \quad n = 0, 1, 2, \ldots$$

Letting

$$T_{f,j}^{*n} = T_f^*((j-\tfrac{1}{2})\Delta x^*, n\Delta\theta^*),$$

$$T_{s,j}^{*n} = T_s^*((j-\tfrac{1}{2})\Delta x^*, n\Delta\theta^*),$$

$$R_f = \tfrac{1}{2} N_{tu}\Delta x^*, R_{s1} = \frac{\lambda_1 \Delta\theta^*}{2\Delta x^{*2}}$$

and

$$R_{s2} = N_{tu}\frac{\Delta\theta^*}{2},$$

equations (1) and (2) can be replaced by

$$T_{f,j}^{*n} = \frac{(1-R_f)T_{f,j-1}^{*n} + R_f(T_{s,j}^{*n} + T_{s,j-1}^{*n})}{1+R_f},$$
$$j = 1, 2, \ldots, m+1, \quad n = 0, 1, 2, \ldots, \tag{6}$$

$$T_{s,j}^{*n+1} = T_{s,j}^{*n} + R_{s1}((T_{s,j+1}^{*n} - 2T_{s,j}^{*n} + T_{s,j-1}^{*n}) + (T_{s,j+1}^{*n+1} - 2T_{s,j}^{*n+1} + T_{s,j-1}^{*n+1})) + R_{s2}((T_{f,j}^{*n} - T_{s,j}^{*n}) + (T_{f,j}^{*n+1} - T_{s,j}^{*n+1})),$$
$$j = 1, 2, \ldots, m, \quad n = 0, 1, 2, \ldots \tag{7}$$

The initial condition, equation (3), and the boundary conditions, equations (4) and (5b), are

$$T_{s,j}^{*n} = 0, \quad j = 1, 2, \ldots, m, \tag{8}$$

$$T_{s,0}^{*n} = T_{s,1}^{*n} \quad \text{and} \quad T_{s,m+1}^{*n} = T_{s,m}^{*n}, \quad n = 0, 1, 2, \ldots, \tag{9}$$

$$T_{f,0}^{*n} = 2(1 - \exp(-n\Delta\theta^*/\tau^*)) - T_{f,1}^{*n}, \quad n = 0, 1, 2, \ldots \tag{10}$$

A computer program was written to solve equations (6)–(10). The term $(T_{f,j}^{*n+1} - T_{s,j}^{*n+1})$ in equation (7) was evaluated by iteration and treated as a known quantity in the computer program. It has been shown that two or three iterations would suffice for the mesh sizes. The numerical values of T_f^* at $x^* = 1$, $(T_{f,m+1/2}^{*n})$, should be evaluated by interpolation after the values of T_f^* at all mesh points were obtained.

Obviously, the values thus obtained at $\tau^* = 0$ and $\lambda_1 = 0$ should be identical to those given by Schumann's solution, and the values obtained at $\tau^* \neq 0$ and $\lambda_1 = 0$ should be identical to those given by Liang and Yang's solution. To check the accuracy of the numerical calculation, we compared the calculated values of the above two limiting cases, respectively. It has been found that the results are consistent for $\Delta x^* = 0.02$ and $\Delta\theta^* = 0.01$. The theoretical outlet fluid temperature response curves for $\tau^* = 0.05$ and 0.1 at different λ_1 calculated by this program are presented in Figs. 1(a) and (b), respectively.

THE EFFECT OF LONGITUDINAL CONDUCTION ON TEST RESULTS

On the basis of the numerical solution, we analysed the effect of longitudinal conduction on the selected

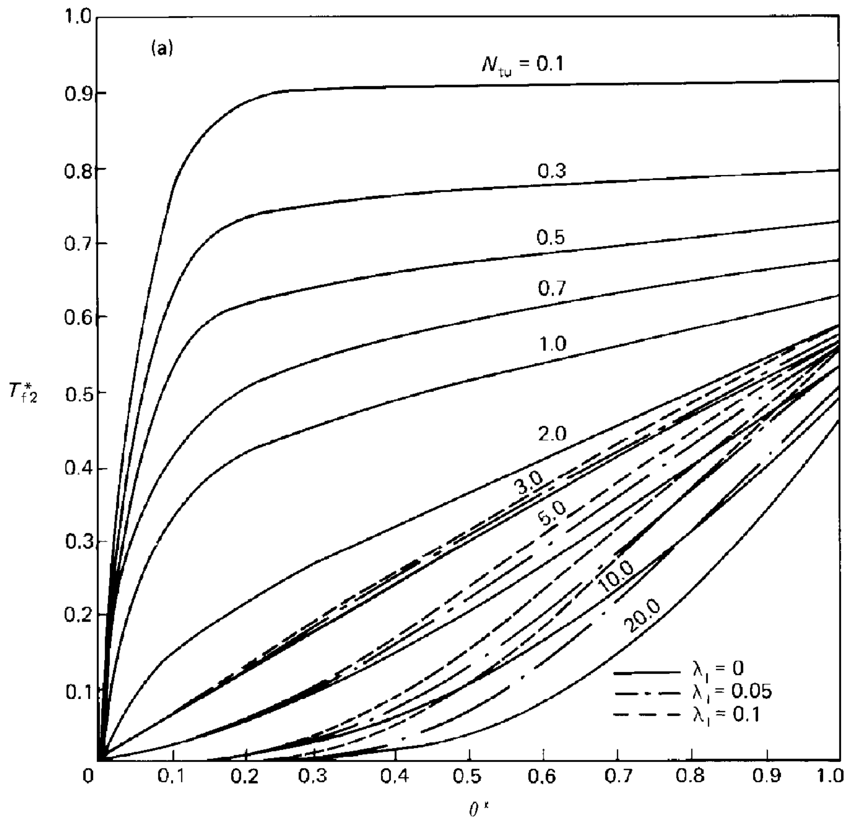


FIG. 1(a). The theoretical outlet fluid temperature response curves for $\tau^* = 0.05$ at different λ_l.

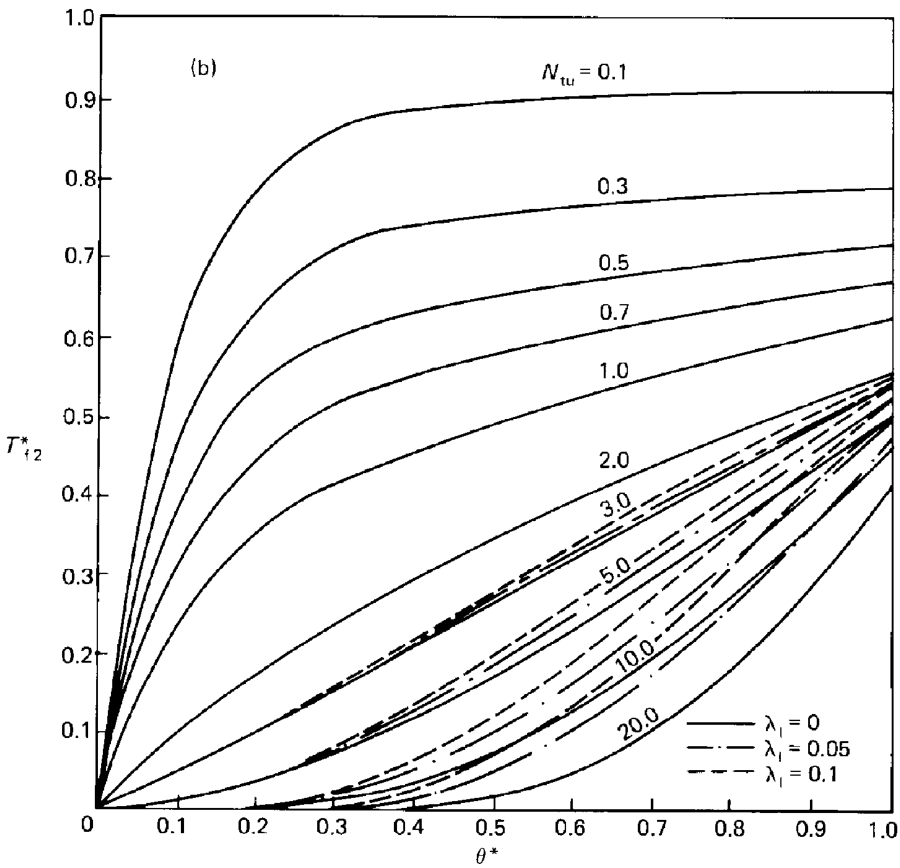


FIG. 1(b). The theoretical outlet fluid temperature response curves for $\tau^* = 0.1$ at different λ_l.

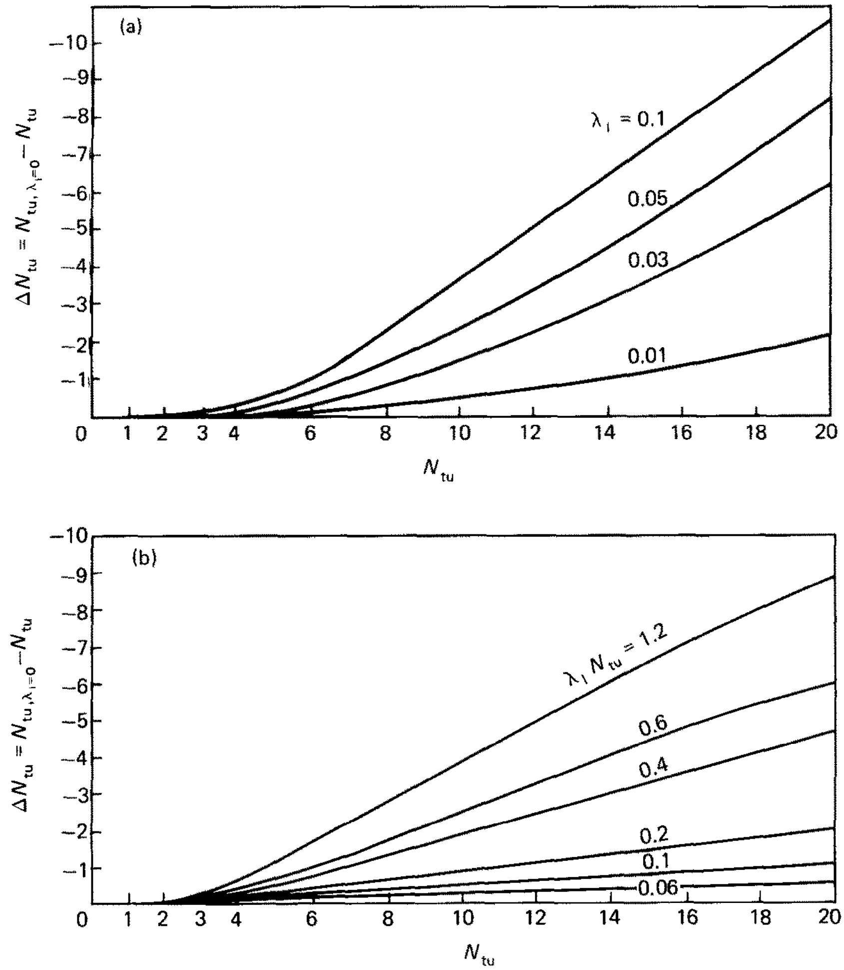


FIG. 2. The effect of longitudinal heat conduction on the selected point matching technique results.

point matching technique results. The calculated results are presented graphically in Fig. 2. Figure 2 shows that: (1) the longitudinal conduction has a negligible effect for $N_{tu} < 3$ or $\lambda_l N_{tu} < 0.06$; (2) the longitudinal conduction effect must be considered for both $N_{tu} \geqslant 3$ and $\lambda_l N_{tu} \geqslant 0.06$, or else the N_{tu} results obtained will be on the low side, and this error will increase remarkably with increases of the values of N_{tu} and $\lambda_l N_{tu}$.

THE EFFECT OF THE DEVIATION FROM A STEP CHANGE ON TEST RESULTS

The deviation of the actual inlet fluid temperature, $T^*_{f1}(\theta^*)$, from the step change for the heating case can be expressed by

$$I = \int_0^\infty (1 - T^*_{f1}(\theta^*))\, d\theta^*,$$

and the effect of a given I on the N_{tu} results can be evaluated using the numerical calculations. For a particular $T^*_{f1}(\theta^*)$ as used in both ref. [9] and this paper, the results of such a computation for $\lambda_l = 0$ are shown in Fig. 3. It can be clearly seen from Fig. 3 that the effect of the deviation from a step change on the test results is outstanding. Therefore, it is not proper to use the assumption of a step change which actually can never be achieved as the inlet fluid temperature condition.

THE OPTIMUM MATCHING TIME AND THE MODIFIED SELECTED POINT MATCHING TECHNIQUE

In the selected point matching technique, the heat transfer performances are determined by matching the measured value $T^*_{f2,\exp}(\theta^*)$ selected at time θ^* with the corresponding theoretical value. When the difference between the measured value and the corresponding theoretical value is within an accepted value (<0.005), the value of N_{tu} assumed in calculating the theoretical value T^*_{f2} is taken to be the result at this time. Then the $T^*_{f2,\exp}(\theta^*)$ of a new point at a larger time is selected and the above procedure is repeated. Finally, the arithmetical mean value of the results at different times is considered to be the value of N_{tu} for this test run. In Liang and Yang's technique, five points were selected for matching which were equally spaced on the outlet

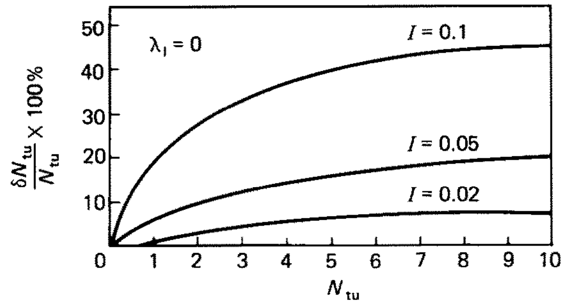


FIG. 3. The effect of the deviation from a step change on test results.

fluid temperature response curve for response times between 1–9 s. However, there is always a certain uncertainty ($\approx$0.2 K) for the measured outlet fluid temperature, therefore the matching time should be selected in such a manner that will minimize the effect of this uncertainty. For this technique, the sensitivity to temperature measurement uncertainty can be determined as

$$E = \frac{|\delta N_{tu}/N_{tu}|}{|\delta T_{f2}^*|} = \frac{1}{N_{tu}}\left|\left(\frac{\partial N_{tu}}{\partial T_{f2}^*}\right)\right|, \tag{11}$$

where E is the amplification factor resulting from the uncertainty in temperature measurement. It has been shown that the amplification factor, E, is quite different at different matching times for any given N_{tu}. Therefore, whether the selected matching time is suitable or not has a great influence on the accuracy of the test results. The analysis predicts that there exists an optimum matching time for a given N_{tu}, at this time the value of $|(\partial N_{tu}/\partial T_{f2}^*)|$ is at a minimum. The optimum matching time as a function of N_{tu}, τ^* and λ_l is obtained using a numerical calculation and is presented graphically in Fig. 4. The matching time interval can be selected from $\theta_{op}^* - \Delta\theta^*$ to $\theta_{op}^* + \Delta\theta^*$, where $\Delta\theta^* = 0.05–0.0012N_{tu}$. If the matching is done according to the matching time recommended in Fig. 4, it is expected to obtain the best test results for an uncertainty in temperature measurement.

Accordingly, from Figs. 2 and 4, the modified selected point matching technique can be summarized below as:

(1) For $N_{tu} < 3$ or $\lambda_l N_{tu} < 0.06$, we may use the analytical solution neglecting longitudinal heat conduction [9] as the basis of the technique and select five points to match which are equally spaced within the time interval for $\lambda_l = 0$ recommended in Fig. 4.

(2) For both $N_{tu} \geqslant 3$ and $\lambda_l N_{tu} \geqslant 0.06$, we must use the numerical solution including longitudinal heat conduction as the basis of the technique and select five points to match which are equally spaced within the time interval for the given λ_l and τ^* recommended in Fig. 4.

AN EMPIRICAL FORMULA TO CORRECT THE LONGITUDINAL HEAT CONDUCTION EFFECT

An empirical formula to correct the effect of longitudinal heat conduction for the case of $N_{tu} \geqslant 3$ and $\lambda_l N_{tu} \geqslant 0.06$ has been obtained as:

$$N_{tu} = \begin{cases} N_{tu_o}, & \text{for } N_{tu_o} < 2.88, \\ N_{tu_o} + 6.4\lambda_l^{1.68}(N_{tu_o} - 2.88)^{2.4} + 0.2\lambda_l^{0.5}N_{tu_o}, & \text{for } N_{tu_o} \geqslant 2.88, \end{cases} \tag{12}$$

where N_{tu_o} is a value of N_{tu} which is obtained by matching the measured value of the outlet fluid temperature with Liang and Yang's solution (see ref. [9], equation (11)). The applicable range of this formula is $\tau^* \leqslant 0.1$, $\lambda_l \leqslant 0.1$, and $N_{tu} \leqslant 20$. It has been shown that the uncertainty of this formula is about $\pm 2\%$.

The procedure of the approximate technique using the empirical formula is as follows:

(1) Select five measured values of the outlet fluid temperature which are equally spaced within the time interval recommended in Fig. 4 for $\lambda_l = 0$ and then match them with the corresponding theoretical values calculated from Liang and Yang's analytical solution, respectively, and then determine their results.

(2) The arithmetical mean value of the results is taken as the value of N_{tu_o}.

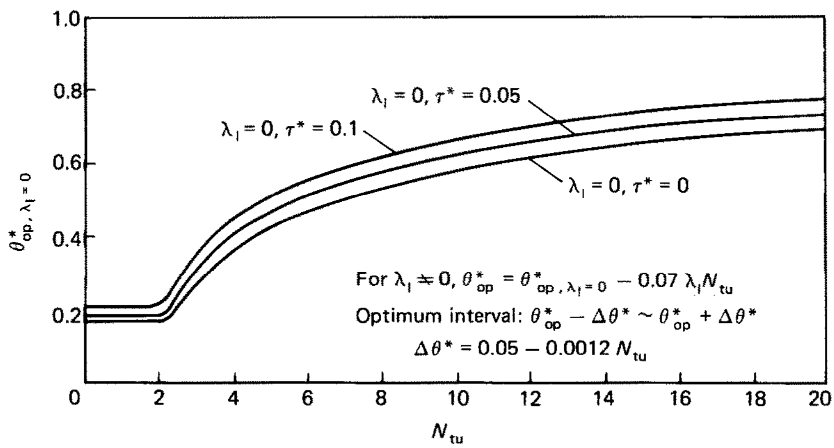


FIG. 4. Recommended matching time for best test accuracy.

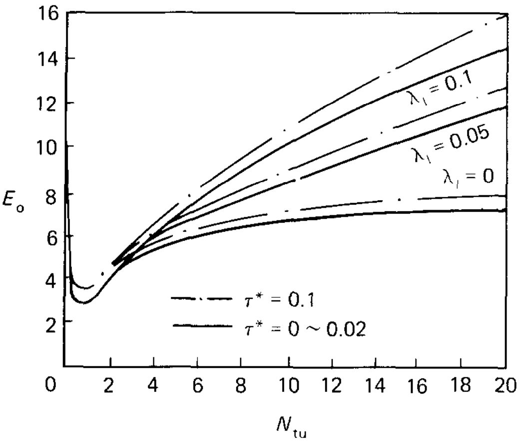


FIG. 5. The amplification factor, E_0, dependence with respect to N_{tu} at different λ_l.

(3) The reliable N_{tu} result is obtained by equation (12).

EFFECT OF UNCERTAINTY IN TEMPERATURE MEASUREMENT TO THE N_{tu} RESULTS

When the heat transfer performance is determined by the selected point matching technique, the error, δT^*_{f2}, in the outlet fluid temperature measurement influences directly the accuracy of the N_{tu} results. The sensitivity to this temperature measurement uncertainty can be determined from equation (11). When the selected point matching is carried out according to the matching time recommended in Fig. 4, the amplification factor has a minimum value (denoted as E_0). According to numerically calculated results, the dependence of the minimum amplification factor, E_0, with respect to N_{tu} is shown in Fig. 5 for two inlet fluid temperature conditions at $\lambda_l = 0, 0.05$, and 0.1, respectively. It can be seen from Fig. 5 that the minimum amplification factor, E_0, is not very sensitive to the inlet fluid temperature condition, and the effect of λ_l is greater for $N_{tu} > 3$ and increases as the value of N_{tu} increases.

It can be concluded from Fig. 5 that, if an optimum matching time recommended in Fig. 4 is selected and used in testing, the relative N_{tu} error for an uncertainty in temperature measurement ($\delta T^*_f \approx 0.012$) can be held at about 4–14% for $0.2 < N_{tu} < 20$.

EFFECTS OF ERRORS IN PHYSICAL PROPERTIES TO THE N_{tu} RESULTS

It is known that the measurement errors of various physical properties exert some effects on the theoretical value of the outlet fluid temperature, T^*_{f2}, through the dimensionless parameters, λ_l and θ^*, thereby errors in test results will come about. It has been shown from analysis that the N_{tu} results are not effected by a probable error in λ_l, but are quite sensitive to an error in θ^*. The sensitivity of the N_{tu} results to the error in θ^* is plotted in Fig. 6. It is seen that the relative error of the

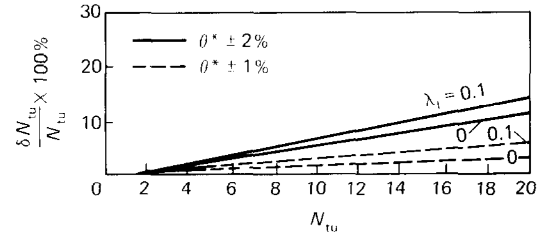


FIG. 6. The effect of the measurement errors in physical properties on the N_{tu} results by θ^*.

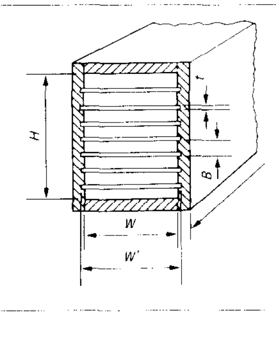
N_{tu} value as a result of the error in θ^* is less than that by the temperature measurement uncertainty, and the effect is negligible for the case of about a $\pm 1\%$ error in θ^*.

TESTING RESULTS OBTAINED BY THE MODIFIED SELECTED POINT MATCHING TECHNIQUE

The test core consisting of a number of aluminum plates to form parallel flow channels (see Table 1) was built and tested to establish the validity of the modified selected point matching technique. Before the heat transfer performance of surfaces was experimentally determined, it was necessary to measure the temperature response of inlet air to a step power input to a heating screen at different air velocities. The inlet fluid temperature boundary condition was determined by equation (5b). During the experiment, the air steadily flowed through the test core. After the steady-state condition had been established, an electric current sufficient to heat up the incoming air by about 15 K was suddenly applied to the heating screen, and the outlet fluid temperature dependence with respect to time $T^*_{f2,exp}$ was continuously recorded by the printer downstream of the test core.

The heat transfer performance was determined by the modified selected point matching technique and the test results are compared with Stephen's solution under the constant wall temperature boundary condition [10] in Fig. 7 to verify the test accuracy. At the same time the matching results from Liang and Yang's solution and the approximate technique are also shown in Fig. 7. It can be seen from Fig. 7, that the matching may be made by Liang and Yang's solution for $N_{tu} < 3$ or $\lambda_l N_{tu} < 0.06$ only, and the effect of longitudinal heat

Table 1. Specifications of the test core



t: 1.0 mm
B: 3.38 mm
W: 0.20 m
W': 0.21 m
H: 0.30 m
L: 0.499 m
A: 17.56 m^2
A_c: 0.0424 m^2
A_{fr}: 0.06 m^2
D_h: 0.00476 m
N_{tu}: 2.3–8.0
λ_l: 0.02–0.069

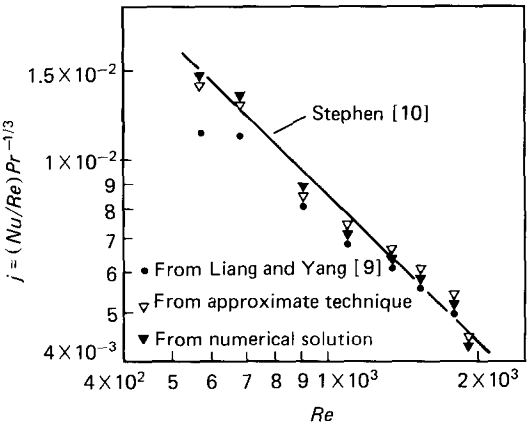


FIG. 7. Testing results of the plate test core.

conduction should be considered for both $N_{tu} \geqslant 3$ and $\lambda_l N_{tu} \geqslant 0.06$. In addition, it may be seen also from Fig. 7 that the results of approximate matching from the empirical formula (12) agree well with the matching results from the numerical solution. This is a proven fact that the approximate technique with the empirical formula (12) is a convenient and reliable technique for cases where the longitudinal heat conduction effect have to be considered.

CONCLUSION

Liang and Yang's modified single-blow transient technique fails for both $N_{tu} \geqslant 3$ and $\lambda_l N_{tu} \geqslant 0.06$ because longitudinal heat conduction was neglected in their analysis [9]. To extend Liang and Yang's analysis, a 'modified selected point matching technique' is developed, in which the heat conduction effect is taken care of and the optimum matching time interval is recommended to assure the best test accuracy. To save computing time, an empirical formula is obtained on the basis of the numerical computations, by which the N_{tu} test results can be corrected for the effect of heat conduction easily. It has been shown that the results thus obtained are sufficiently accurate for practical uses. It also gives the effects of the probable errors in temperature measurement and physical properties to N_{tu} values.

The validity of this modified technique is confirmed by the good agreement between the experimental results and the theoretically predicated results [10].

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UNE TECHNIQUE MODIFIEE A POINTS SELECTIONNES POUR COMPARER LES SURFACES D'ECHANGEURS COMPACTS

Résumé—Une technique transitoire tenant compte de la conduction thermique longitudinale est développée dans laquelle $T^*_{f1}(\theta^*)$ déterminé expérimentalement est utilisé comme température d'entrée du fluide. On montre que l'effet de conduction longitudinale doit être inclus à la fois pour $N_{tu} \geqslant 3$ et $\lambda_l N_{tu} \geqslant 0{,}06$ et qu'il existe un intervalle de temps optimal. Une formule empirique pour corriger de l'effet de conduction à $N_{tu} \leqslant 20$, l'intervalle de temps optimal et une analyse des incertitudes sont données. La validité de cette technique est confirmée par le bon accord entre les données d'essais et les résultats calculés.

EIN MODIFIZIERTES VERFAHREN DER 'PUNKTWEISEN ANPASSUNG' ZUR UNTERSUCHUNG KOMPAKTER WÄRMEÜBERTRAGERFLÄCHEN

Zusammenfassung—Es wurde ein instationäres Verfahren entwickelt, welches den Längs-Wärmeleitungs-Effekt berücksichtigt und ein experimentell bestimmtes $T^*_{f1}(\theta^*)$ als Bedingung für die Fluid-Eintrittstemperatur verwendet. Es wird gezeigt, dass für $N_{tu} \geqslant 3$ und $\lambda_l N_{tu} \geqslant 0{,}06$ der Längsleitungs-Effekt berücksichtigt werden muss und dass ein optimales Anpassungs-Intervall für die Zeit besteht. Weiter werden eine empirische Gleichung für die Korrektur des Wärmeleitungs-Einflusses für $N_{tu} \leqslant 20$ und das optimale Anpassungs-Intervall für die Zeit angegeben; eine Fehlerbetrachtung ist angeschlossen. Die Brauchbarkeit des Verfahrens wird durch die gute Übereinstimmung zwischen den experimentellen Daten und den berechneten Ergebnissen bestätigt.

МОДИФИЦИРОВАННЫЙ МЕТОД ПОДГОНКИ ДЛЯ ИССЛЕДОВАНИЯ ПОВЕРХНОСТЕЙ КОМПАКТНЫХ ТЕПЛООБМЕННИКОВ

Аннотация—Для учета продольной теплопроводности разработан нестационарный метод, в котором экспериментально определяемая величина $T^*_{f1}(\theta^*)$ используется как условие для температуры жидкости на входе. Показано, что продольная теплопроводность должна учитываться как при $N_{tu} \geq 3$, так и при $\lambda_1 N_{tu} \geq 0{,}06$, при этом существует оптимальный подгоночный временной интервал. Приведены эмпирическая формула для учета эффекта теплопроводности при $N_{tu} \leq 20$, оптимальный подгоночный временной интервал и анализ неопределенности. Справедливость метода подтверждается хорошим совпадением тестовых данных с результатами расчетов.