SIMILARITY OF NON-NEWTONIAN FLOWS. V.* FLOW AND HEAT TRANSFER IN AN ANNULAR DUCT

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The concept of pseudosimilarity for a given hydrodynamic and transport problem is tested by comparing the exact solution of the mathematical model of flow and heat transfer in an annular duct for the Bingham, Eyring, and Ree–Eyring rheological models with the solution for the power-law model. On the basis of verified hypothesis of pseudosimilarity a generalized transport correlation is proposed, design graphs are presented and a detailed procedure for calculation of heat exchange is given.

Laminar flow through a duct of annular cross-section is one of few one-dimensional flow situations which do not belong into the category of MR-flows[1–3]. Therefore, to solution of this hydrodynamic problem for various non-Newtonian materials a great attention was paid with respect to individual specified models of viscosity functions[4–10] as well as to generalized considerations not limited to specified model [3,11–15]. Unlike this, the problems of heat transfer into non-Newtonian liquid in laminar flow through an annular duct were solved mathematically only for the power-law[16–18] flow model.

This study is based on an exact solution of the heat transfer problem for the temperature independent non-Newtonian flow through the annulus for the Bingham, Eyring, and Ree–Eyring models[19], on the conception of pseudosimilarity[2], and on the possibility to describe the process of laminar heat transfer in channels by a simple three-parameter model[20,21].

PSEUDOSIMILARITY OF FLOW THROUGH THE ANNULUS

Dimensionless mathematical (analytical) model of a laminar, temperature independent non-Newtonian flow through an annulus (Fig. 1) can be written as a system of relations[14,15] for the dimensionless shear stress

$$\vartheta = \vartheta(\xi) \equiv A(\xi^2 - \lambda^2)/\xi\,, \tag{1}$$

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for the normalized volumetric flow rate B

$$B = B(A, \varkappa) \equiv 1/(1 - \varkappa^2) \int_{\varkappa}^{1} p[\vartheta(\xi)]\, \xi^2 \,\mathrm{d}\xi\,, \tag{2}$$

for the normalized velocity profile

$$w = w(\xi) = (1/B) \int_{\xi}^{1} p[\vartheta(\xi)] \,\mathrm{d}\xi \tag{3}$$

and the binding condition for the eigenvalue λ

$$B\, w(\varkappa) = 0 = \int_{\varkappa}^{1} p[\vartheta(\xi)] \,\mathrm{d}\xi\,, \tag{4}$$

where $p[\vartheta]$ is the normalized viscosity function.

According to definition[2], n^* is given by the relation

$$\frac{1}{n^*} = \frac{A}{B}\left(\frac{\partial B}{\partial A}\right)_{\varkappa}. \tag{5}$$

In the appendix it is shown that $n^* = n^*(A, \varkappa)$ can according to definition (5) be expressed in the form

$$\frac{1}{n^*} = \frac{p(1) + \varkappa^3\, p(\varkappa)}{B} - 3(1 - \varkappa^2) + \lambda^2 +$$

$$+ \frac{1}{B}\, \frac{(p(1) - \varkappa\, p(\varkappa))^2}{p(1)/(1 + \lambda^2) - [\varkappa\, p(\varkappa)]/(\lambda^2 + \varkappa^2) + \int_{\varkappa}^{1} p[\vartheta(\xi)]/[(\xi^2 - \lambda^2)\,(\xi^2 + \lambda^2)^2] \,\mathrm{d}\xi}\,. \tag{6}$$

The postulates of pseudosimilarity can be written in the form: Kinematic pseudosimilarity:

$$w \approx w_a(\xi, \varkappa, n^*)\,, \tag{7}$$

where w_a is the known solution of Fredrickson and Bird[5] for the power-law model $p[\vartheta] = \vartheta^{1/n}$. Dynamic pseudosimilarity: This aspect is represented by the requirement $\vartheta(1) \approx A(1 - \lambda_a^2)$, $\vartheta(\varkappa) = -A(\lambda_a^2 - \varkappa^2)/\varkappa$, for which – according to Eq. (1) – sufficient condition is the validity of relation

$$\lambda \approx \lambda_a(\varkappa, n^*)\,, \tag{8}$$

where $\lambda_a(\varkappa, n^*)$ is the known solution[5] of Eq. (4) for the power-law model; Rheological pseudosimilarity:

$$n^* \approx n_{rh}[\nu A] , \tag{9}$$

where ν is chosen so that $\tau_w = \nu P_c$ would equal the mean integral value of shear stresses on both walls, *i.e.* so that $(\tau_w L\pi R^2(1 + \varkappa^2))$ represents the overall force with which the flowing liquid acts on the duct walls

$$\nu = \frac{A(1 + \varkappa)}{|\vartheta(1)| + \varkappa\,|\vartheta(\varkappa)|} = \frac{1}{1 - \varkappa} . \tag{10}$$

Results of testing the kinematic pseudosimilarity are presented in Fig. 2 as the dependence of

$$w_{MAX} = w(\lambda) = \frac{1}{B}\int_{\varkappa}^{1} p[\vartheta(\xi)]\,d\xi \tag{11}$$

on n^* for the power-law, Bingham, Eyring and Ree–Eyring models for the selected value $\varkappa = 0{\cdot}25$. Analogically are presented in Fig. 3 the testing results of dynamic

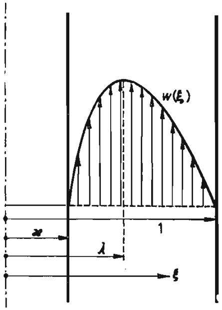

FIG. 1

Arrangement of Axial Flow Through an Annular Duct

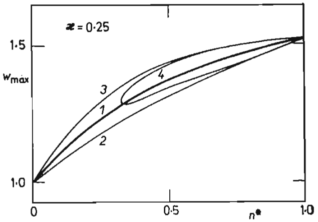

FIG. 2

Kinematic Pseudosimilarity for Axial Flow through Annulus

Dependence of normalized maximum velocity on apparent flow index for *1* power-law model, *2* Bingham model, *3* Eyring model, *4* Ree–Eyring model for Ey = 100.

pseudosimilarity. Results of testing the rheological pseudosimilarity are given in Fig. 4 only for the case of the Ree-Eyring model as a comparison of the dependence of n^* and $n_{rb}[A/(1-\varkappa)]$ on parameter A. Dimensional and related dimensionless relations for the course of rheological models under consideration in the form of $\vartheta(p)$, and the inverse functions $p(\vartheta)$ are given in Table I and are plotted in Fig. 5.

Pseudosimilarity for Laminar Heat Transfer

We have shown recently[18,20] that for the temperature independent Newtonian and power-law flow through the tube, slit and annular duct the heat transfer problem can be described integrally in the whole range of dimensionless lengths z of the heat transfer duct

$$z = \frac{xk}{\varrho c_p U R^2 (1 - \varkappa^2)} \tag{12}$$

by approximate relations in the form

$$t_M = \frac{T_M - T_w}{T_0 - T_w} \begin{cases} 1 - \dfrac{1 \cdot 615 (w_0')^{1/3} z^{2/3}}{1 + \varkappa}; & z < 0 \cdot 1 \quad (13a) \\ t_{M1} \cdot \exp[-b_1^2 z]; & z > 0 \cdot 1 \quad (13b) \end{cases}$$

which includes only three numerical parameters t_{M1}, b_1^2, w_0' generally dependent only on the form of the velocity profile and thus also on rheological properties of the

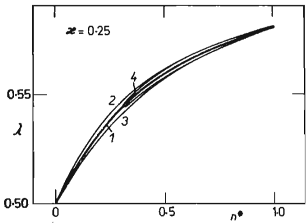

Fig. 3

Kinematic Pseudosimilarity for Axial Flow through Annulus; Dependence of Parameter on Apparent Flow Index

Individual curves are denoted in the same way as in Fig. 2.

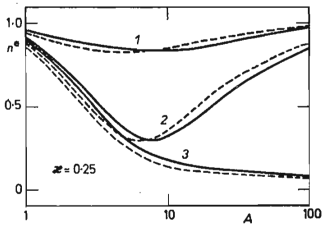

Fig. 4

Rheological Pseudosimilarity for Axial Flow through Annulus

Solid curves n^*, dashed curves n_{rh}, *1* Ree-Eyring model, Ey = 1, *2* Ree-Eyring model, Ey = 100, *3* Eyring model.

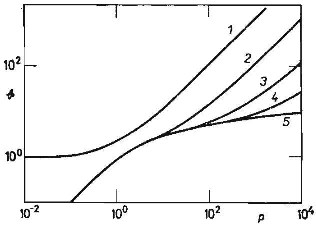

FIG. 5

Course of Viscosity Functions According to Some Models

1 Bingham model, *2*, *3*, *4* Ree–Eyring model for Ey = 10, 100, 1 000; *5* Eyring model.

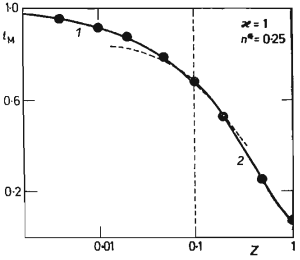

FIG. 6

Calculated Points of Dimensionless Mean Mixing Temperature $t_M(z)$ in Dependence on Axial Coordinate for Heat Transfer into Non-Newtonian Liquids $n^* = 0.25$ in Flat Channel

1 Relation (*13a*), 2 relation (*13b*); ● Eyring model, ○ power-law model, ◒ Bingham model.

TABLE I

Transformation of Models of Viscosity Functions to Dimensionless Form

Model	Dimensional form	Dimensionless form
Bingham	$\tau = \tau_I + \mu_I \cdot D$	$\vartheta = 1 + p$
Eyring	$\tau = \tau_I \cdot \operatorname{arsinh}(D/D_I)$	$\vartheta = \operatorname{arsinh}(p)$
Ree–Eyring	$\tau = \frac{\tau_I/D_I}{1 + \mathrm{Ey}} D + \frac{\tau_I \mathrm{Ey}}{1 + \mathrm{Ey}} \operatorname{arsinh}(D/D_I)$	$\vartheta = \frac{1}{1 + \mathrm{Ey}} p + \frac{\mathrm{Ey}}{1 + \mathrm{Ey}} \operatorname{arsinh}(p)$

material. From Figs 6–8 where the approximate dependences t_M on z according to the three-parameter model (*12*), (*13a*), (*13b*) are plotted together with points corresponding to exact solutions[19] for the Eyring, power-law and Bingham models, is obvious that the proposed three-parameter model also fits the non-power-law models of viscosity function very well. The approximative three-parameter models (*13a*), (*13b*) can be thus taken as a base for the corresponding generalized transport correlation. (Where it

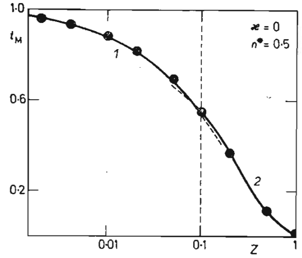

FIG. 7

Dependence of $t_M(z)$ for Heat Transfer into Non-Newtonian Liquids $n^* = 0.5$ in Tube

The curves and points see Fig. 6.

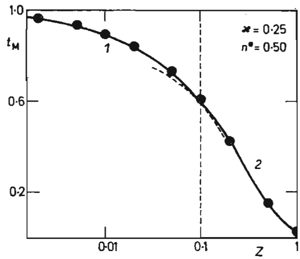

FIG. 8

Dependence of $t_M(z)$ for Heat Transfer into Non-Newtonian Liquids $n^* = 0.25$ in Annular Duct $\varkappa = 0.25$

The curves and points see Fig. 6.

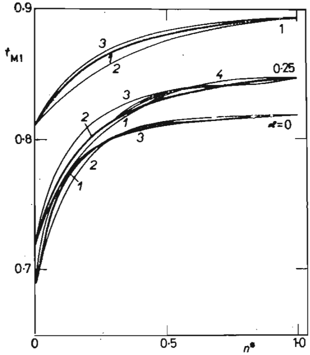

FIG. 9

Dependence of Constant t_{M1} in Relation (*13b*) on n^* for Different Non-Newtonian Models and Different Geometries

1 Power-law model, *2* Bingham model, *3* Eyring model, *4* Ree–Eyring model Ey = = 100.

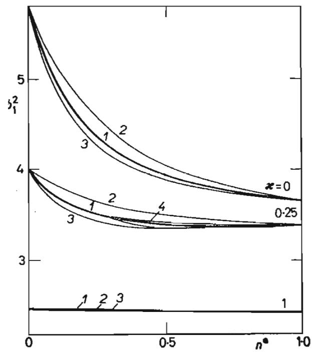

FIG. 10

Dependence of Constant b_1^2 in Relation (*13b*) on n^* and $\varkappa$

The curves see Fig. 9.

was in Figs 6–8 not possible to distinguish between individual points corresponding to an exact solution, only the Eyring solution was plotted). This conclusion is also supported by extensive numerical material[19] whose results are summarized in Figs 9–11. These figures show, in dependence on n^*, the values of constants of the three-parameter heat transfer model *(13a)*, *(13b)* for different models of viscosity function. The values of parameters for the Ree–Eyring model are as before, situated in the region limited by extreme values of these parameters for the Eyring and Bingham models. This fact is presented in Figs 9–11 only for the annulus with $\varkappa = 0.25$. We have chosen this value as an example because for $\varkappa \to 1$ the whole problem becomes an analogy of the flat duct and already for $\varkappa > 0.8$ the results do not much differ; for $\varkappa = 0$ the whole problem then becomes the analogy of the tube. Values $\varkappa \in (0.25; 0.75)$ thus correspond to technically interesting geometries of the annular duct for which the corresponding transport problems cannot be approximated by the solution for flat duct or tube.

Use of a Generalized Transport Correlation

On the basis of Figs 9–11 the corresponding heat transfer problem can be solved for a given geometry of the annular duct L, R, $\varkappa$, for a given temperature on the outside wall T_w, for thermally insulated inside wall, for known inlet temperature of the liquid T_0, and volumetric flow-rate Q, for known material constants of the liquid ϱ, c_p, k and for known course of the viscosity function, *i.e.* the mean calorimetric liquid temperature at the outlet from the exchanger can be determined. The dimensionless length of the exchanger z will be determined from Eq. *(12)*, *i.e.* as

$$z = \frac{\pi L k}{\varrho c_p Q} . \qquad (14)$$

To be able to use the performance charts,* there remains to determine for the given parameters Q, R, $\varkappa$ and the known course of the viscosity functions $\tau = \tau[D]$ the value of parameter n^*.

For the power-law model the dimensionless velocity gradient on the heat transfer surface

$$w_0' = -\left.\frac{dv_z}{dr}\right|_{r=R} \frac{\pi R^3 |1 - \varkappa^2|}{Q} \qquad (15a)$$

is a function of n and $\varkappa$. This dependence is plotted in Fig. 11. The first estimate w_0' can be obtained with the assumption $n = 1$ according to the known relation

$$w_0' = 4 \frac{1 + (1 - \varkappa^2)/(\ln \varkappa^2)}{1 + \varkappa^2 + 2(1 - \varkappa^2)/(\ln \varkappa^2)} \qquad (16)$$

for Newtonian flow through the annulus. For thus determined first estimate of w_0' we can calculated the value of velocity gradient, *i.e.* of the shear rate on the heat transfer surface

* See also Figs 9–11 of the work[20].

$$D_w = - \frac{dv_z}{dr}\bigg|_{r=R} = w'_0 \frac{Q}{\pi R^3 |1 - \varkappa^2|} \,. \qquad (15b)$$

For the value $D = D_w$ the value of the slope is read from the rheogram $\tau = \tau[D]$ and the first estimate n^* is determined as

$$n^* = n_{rh} \equiv \frac{D}{\tau} \frac{d\tau[D]}{dD} = \frac{d \ln \tau}{d \ln D}\,; \qquad (17)$$

for thus determined n^* we read from Fig. 11 the value w'_0 and repeat the determination of D_w according to (*15b*) and of n^* according to (*17*) until the estimated values D_w considerably change. The result of this numerical-graphical iteration is the value n^* determined, according to the accuracy of the rheogram and graphical operations, with an accuracy $\pm 0{\cdot}05$. Graphical operation can be made more accurate if we prepare in advance a graph of dependence $n_{rh} = n_{rh}[D]$. For the estimated value n^* we read from the graphs 9–11 the values of parameters t_{M1}, b_1^2, w'_0 and by relation (*13a*) and (*13b*) determine the value t_M. The outlet mean temperature of the liquid is given by relation

$$T_M = t_M \,.\, (T_0 - T_w) + T_w \,. \qquad (18)$$

Obviously it is also possible to solve the inverse problem, *i.e.* to look for the length of the exchanger necessary for bringing the liquid temperature to the one given in advance. The proce-

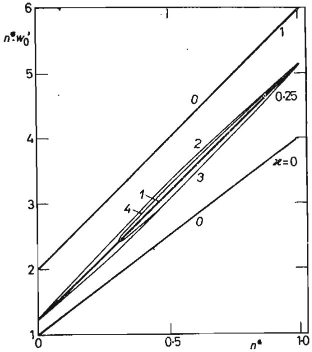

FIG. 11

Dependence of Product of Dimensionless Velocity Gradient on the Heat Transfer Wall w'_0 (constant in relation (*13a*)) and n^* on n^* and $\varkappa$

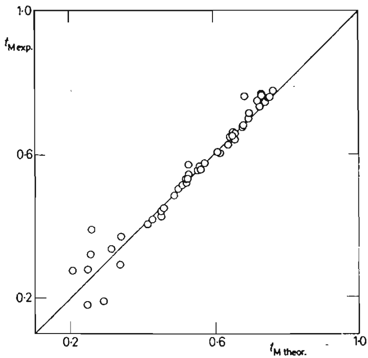

FIG. 12

Comparison of Mean Mixing Dimensionless Temperatures t_{Mexp} Determined from Experimental Data for Heating of 30% Suspension of Kaoline in Water in an Annular Duct with $\varkappa = 0{\cdot}72$ with Calculated Values t_{Mth}

dure of finding the parameters t_{M1}, b_1^2, w_0' remains the same. Whether we use for calculation relation *(13a)*

$$z = \frac{(1 - t_M)^{3/2} (1 + \varkappa)^{3/2}}{1{\cdot}615^{3/2} (w_0')^{1/2}}, \tag{19a}$$

or relation *(13b)*

$$z = \frac{1}{b_1^2} \ln \left(\frac{t_{M1}}{t_M} \right), \tag{19b}$$

depends on whether $1 \geqq t_M \geqq t_{M0}$ (calculated by relation *(19a)*, or whether $t_{M0} \geqq t_M \geqq 0$ (calculated by relation *19b*), where

$$t_{M0} = t_{M1} \exp(-b_1^2/10) \,. \tag{20}$$

The third problem, *i.e.* how to get in the exchanger of given dimensions and temperature of the wall the suitable flow-rate Q with the required outlet mean temperature, cannot be solved explicitly. The most suitable way is to solve the problem by the above described method for several chosen values Q within limits which we consider reasonable and then to find the proper solution graphically in thus prepared graphical dependence of t_M on Q. Data on pressure drop can be, again on the principles of pseudosimilarity, obtained with the use of a rheogram. For the value D_w the value $\tau_w = \tau[D_w]$ is read from the rheogram and the pressure drop ΔP is calculated from relation

$$(\Delta P + \varrho \,.\, g_z \,.\, \Delta h)/(2L) = \tau_w/(1 - \lambda^2) \,, \tag{21}$$

where Δh is the height difference between both ends of the exchanger which we take in Eq. *(21)* as positive, if the liquid flows in the exchanger downwards, and negative if it flows upwards.

CONCLUSIONS

The presented results are limited to the annular exchanger where the outside wall is kept by external heating or cooling at a constant temperature and the inside wall is insulated. Quite analogous procedure[19] can be used also for the reversed case where the inside, heat transfer wall has a constant temperature while the outside wall is insulated. In this case it is sufficient to accept formally $\varkappa > 1$; the heat transfer surface then again corresponds to relation $\xi = 1$. A serious limitation in this method is the condition of thermal independency of the velocity field which for technically interesting situations is not fulfilled very often. Technically interesting group of materials, for which the presented results can be used without corrections for the temperature dependence of viscosity, are some suspensions. For these materials the proposed correlations can be applied with good accuracy as follows from Fig. 12 in which experimental values t measured with the annulus of $\varkappa = 0{\cdot}72$ are compared for suspensions of kaoline $n_{rh} \in (0{\cdot}15; 0{\cdot}25)$ with the values calculated by the presented method.

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APPENDIX

Local Characteristics of Non-Newtonian Annular Flow

The dimensionless mathematical model of annular flow is presented in this paper as Eqs (*1*)—(*4*). In solving this mathematical model it is necessary to determine in advance the proper value of λ as the root of Eq. (*4*). Suitable numerical methods for solution of this problem have already been discussed[15] in our previous studies. There[15] also the alternative form of a mathematical model for the case is given when the dimensionless viscosity function is expressed explicitly in the form

$$\vartheta = \vartheta[p]\,. \tag{22}$$

Generally considered the determination of parameter n^* is only a part of a more general problem of description of local properties of the system characterized by Eqs (*2*)—(*4*), *i.e.* of the linearized description of dependences of parameters B, λ and the function $w(\xi)$ on independent parameters of the problem A, $\varkappa$ in the vicinity of some in advance given values $A = A_0$, $\varkappa = \varkappa_0$, for a given viscosity function. This local behaviour of the mentioned system in vicinity of given values A_0 and $\varkappa_0$ is determined, if the values of partial derivatives B and λ, according to parameters $\varkappa$ and A, are known.

The respective relations can be obtained by differentiation of Eqs (*2*), (*4*) according to parameters $\varkappa$ and A. Resulting relations can be written in the form

$$\left(\frac{\partial \lambda^2}{\partial \varkappa}\right)_A = -\frac{p(\varkappa)}{B}\frac{1}{H_1}\,, \tag{23}$$

$$A\left(\frac{\partial \lambda^2}{\partial A}\right)_\varkappa = H_3/H_1 - \lambda^2\,, \tag{24}$$

$$\frac{1}{n^*} = \frac{A}{B}\left(\frac{\partial B}{\partial A}\right)_\varkappa = \frac{1}{1-\varkappa^2}\left(H_5 - \frac{H_3^2}{H_1}\right), \tag{25}$$

$$\frac{1}{B}\left(\frac{\partial(1-\varkappa^2)\,B}{\partial \varkappa}\right)_B = -\frac{p(\varkappa)}{B}\left(\varkappa^2 - \frac{H_3}{H_1}\right), \tag{26}$$

where

$$H_i = \int_\varkappa^1 \left(\frac{\partial p[A(\xi^2-\lambda^2)/\xi]}{\partial \xi}\right)_{A,\varkappa} \frac{\xi^i}{\lambda^2+\xi^2}\,\mathrm{d}\xi\,. \tag{27}$$

Since, as can be verified by integration per partes of relation (*27*), the recurrent formula holds

$$H_i = \frac{p(1) - \varkappa^{i-2}p(\varkappa)}{B} - \lambda^2 H_{i-2} - \frac{i-2}{B}\int_\varkappa^1 p[\vartheta(\xi)]\,\xi^{i-3}\,\mathrm{d}\xi \tag{28}$$

and for $k = 5$ and $k = 3$ also the integral relations in Eq. (*28*) are known (relations (*2*)—(*4*)) H_5 and H_3 are given by Eqs

$$H_5 = \frac{p(1) - \varkappa^3 p(\varkappa)}{B} - 3(1-\varkappa^2) - \lambda^2 H_3\,, \tag{29}$$

$$H_3 = \frac{p(1) - \varkappa p(\varkappa)}{B} - \lambda^2 H_1 \tag{30}$$

it remains only to calculate H_1 by a quadrature according to relation

$$H_1 = \frac{1}{B} \int_{p(\varkappa)}^{p(1)} [1 - (1 + (\vartheta[p]/2A\lambda)^2 \{1 + [1 + (2A\lambda/\vartheta[p])^2]^{1/2}\})^{-1}] \, dp \tag{31}$$

for the viscosity function in the form $\vartheta[p]$, or as

$$H_1 = \frac{1}{B} \left(\frac{p(1)}{1 + \lambda^2} - \frac{\varkappa p(\varkappa)}{\lambda^2 + \varkappa^2} + \int_{\varkappa}^{1} p \left[\vartheta(\xi) \frac{\xi^2 - \lambda^2}{(\xi^2 + \lambda^2)^2} d\xi \right] \right) \tag{32}$$

for the viscosity function in the inverse form $p[\vartheta]$. It is an interesting result that for a complete linearized description of the local behaviour according to relations (23)–(26) there remains only to calculate numerically one single quadrature, for H_1.

LIST OF SYMBOLS

$A = (\Delta P . R)/(2 . L . \tau_I)$ normalized pressure drop
$B = Q/(\pi R^3 |1 - \varkappa^2| D_I)$ normalized volumetric flow rate
b_1^2 parameter in relation (13b)
c_p specific heat (cal g^{-1} deg^{-1})
D shear rate, variable in viscosity function (s^{-1})
D_W shear rate on the wall (s^{-1})
D_I material constant, Table I (s^{-1})
Ey Eyring number
g_z projection of gravitational acceleration into flow direction (cm s^{-2})
Δh vertical distance (cm)
k thermal conductivity (cal cm^{-1} s^{-1} deg^{-1})
L length of heat exchanger (cm)
n^* apparent flow index
n flow index
n_{rh} apparent flow index according to rheological pseudosimilarity
$p = D/D_I$ normalized shear rate
$p[\vartheta]$ normalized viscosity function
$p(\xi) = p[A(\xi^2 - \lambda^2)/\lambda]$ profile of normalized shear rate
Q volumetric flow rate (cm^3 s^{-1})
r radial coordinate (cm)
R outside diameter; of annular heat transfer wall (cm)
T_M mean temperature of liquid leaving the exchanger (deg)
T_W temperature of outside annular wall (deg)
T_0 temperature of outlet liquid (deg)
t_M normalized mean temperature, Eq. (2)
t_{M_1} parameter from Eq. (13b)
t_{M0} parameter defined by Eq. (20)
U mean flow velocity (cm s^{-1})

$w(\xi)$ normalized velocity profile
$w_a(\xi)$ estimate of w on basis of kinematic pseudosimilarity
w'_0 normalized velocity gradient on heat transfer (in our case outside) annular wall
w_{MAX} normalized maximum velocity
z normalized axial coordinate, Eq. (*12*)
x axial coordinate, distance from the heat exchanger inlet (cm)
$\vartheta = \tau/\tau_I$ normalized shear stress
$\vartheta(\xi) \equiv [A(\xi^2 - \lambda^2)/\lambda]$ profile of normalized stresses in annulus, ϑ is considered to be the odd function
$\varkappa$ geometric simplex, see Fig. 1
λ ibid
λ_a estimate of λ on basis of pseudosimilarity
ν geometric simplex, Eq. (*10*)
ϱ density (g cm^{-3})
$\xi = r/R$ normalized radial coordinate
τ shear stress, variable in viscosity function (dyn cm^{-2})
τ_w characteristic shear stress at wall (dyn cm^{-2})
τ_I material constant, Table I (dyn cm^{-2})

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