re-ferruling have been that higher loads can be carried without infringing the temperature limits which have been set. As was expected, the first selection of orifice sizes was not effective in permitting removal of all power restrictions. However, learning from the experience of the first unit to be treated (Heysham 1 R1), the re-ferruling patterns on the second and third units (Hartlepool R2 and Heysham I R2) have proved to be better approximations to the required distributions. On these two units, it is not yet known how high a load will be able to be carried without further adjustment. For other reasons, unconnected with the boilers, there are load limitations at present. At these loads, the boilers are still not at their attainable limit.

These experiences on the Hartlepool and Heysham I boilers have shown that performance calculations on complex helical boilers lie at the frontiers of modelling knowledge. Even reasonable approaches to analysis require a very advanced level of computer hardware and software. The relatively poor gas mixing characteristics of this type of plant have become apparent, as has the high sensitivity to dimensional variations between units and to the precision of manufacture and assembly. Large advances have been made in the understanding of the behaviour of these plants. The challenges of correcting temperature and flow distributions have led to the development of new high precision machines and also to the evolution of bore welding techniques to smaller scale and greater accuracy and reproductability than had previously been possible. It is confidently expected that further gains in output from these boiler plants will result from the work planned over the next few years, probably to the point at which the boilers do not become limiting at the designed power station capacity.

DISPERSION OF HOT SPOTS IN STEAM GENERATORS

E.J. ACHENBACH
Institut für Reaktorbauelemente,
Kernforschungsanlage Jülich GmbH,
Jülich, Federal Republic of Germany

Abstract

The streamwise development of hot spots in a helical type heat exchanger has been treated experimentally and theoretically as well. Velocity profiles across the bundle have been measured varying the Reynolds number, Re, from 10^3 to 1.35×10^5. Pressurized air or helium have been applied as coolant.

In an additional series of tests the length scale parameter of the turbulence structure has been determined. It is correlated with the turbulent Peclet number, Pe_t, which occurs in the basic equation as an unknown parameter. Its value was found to be independent of Re ($Pe_t = 8.2$). Introducing this value leads to a good agreement of theoretical and experimental results.

1) Introduction

Hot spots may occur in steam generators due to failure of tubes or to unexpected dry-out effects. This can cause unadmissible thermal stresses of the heat exchanger or of the succeeding components. Therefore it is necessary to be able to predict the dispersion of the hot spot. For this purpose the energy equation must be solved including the effects of turbulent exchange of enthalpy. As will be seen later knowledge is required on the so-called turbulent Peclet number $Pe = u_e \, d/A_q$. This quantity and its dependence on Reynolds number has been measured by several scientists, but the experimental results exhibit departures by more than one order of magnitude. A parameter study, however, has demonstrated that a Peclet number variation by ± 10 % already shows noticible effects on the temperature distribution across the hot spot. Thus it is necessary to obtain more accurate experimental data.

The reason for that the experimental results exhibit such considerable scatter can be seen in the difficulties of the measurement techniques. In all works the exchange coefficient was evaluated from experimental temperature or concentration profiles using first and second order derivations of the curves. The accuracy of this procedure is poor, of course.

In the present paper an alternative method was applied. The mixing coefficient is derived from flow quantities only. It will be shown that the turbulent Peclet number is related to the length scale parameter of the turbulence structure which can be determined by means of hot wire corellation techniques.

2) Basic equations

The dispersion of a hot spot can be described by means of the energy equation (1). Setting the following assumptions

- one-phase-model, tubes are neglected
- steady state flow
- constant mean axial velocity, the mean value of the radial component $v = 0$
- homogeneous turbulence; mixing coefficient, $A_q|_\eta = A_q|_\xi$ are equal in all directions

the equation can be given in the dimensionless form (cylindrical coordinates) by:

$$\frac{\partial\theta}{\partial\xi} = \left(\frac{1}{Pe}+\frac{1}{Pe_t}\right)\left[\frac{\partial^2\theta}{\partial\xi^2}+\frac{\partial^2\theta}{\partial\eta^2}+\frac{1}{\eta}\frac{\partial\theta}{\partial\eta}\right] \qquad (1)$$

where:

temperature	Θ	= (T-Ti) / (Tw-Ti)
radial coordinate	η	= r/d
axial coordinate	ξ	= x/d
Peclet number		$Pe = u_e d/a$
mixing coefficient		A_q [m2/s]
turbulent Peclet number		$P_e = u_e d/A$

The coefficient, 1/Pe, decribes the dispersion due to molecular conductivity, $1/Pe_t \approx 0.1$ the effect by turbulent convection. At high Pe the molecular contribution to the dispersion of heat can be neglected compared to the turbulent effects.

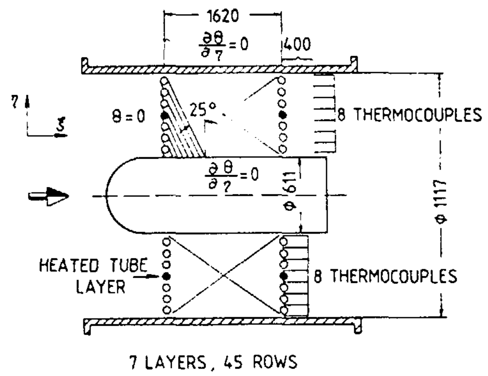

Figure 1
Helical heat exchanger model

Figure 1 shows a sketch of the heat exchanger for which Equ. (1) is to be solved. The boundary conditions are

$$\xi = 0 \quad : \quad \Theta = 0$$
$$\eta = \frac{R_i}{d}\ ;\ \frac{R_a}{d} \quad : \quad \frac{\partial\Theta}{\partial\eta} = 0 \quad \text{(adiabatic walls)} \qquad (2)$$

During the experiments one layer of tubes was heated. To formulate the boundary condition at this position it was assumed that the heat transferred from the tube under the conditions of the actual Stanton number, St, completely mixes in the unit domain of the particular tube and then can be released radially by dispersion. Thus we find

$$\frac{\partial\theta}{\partial\xi}\Big|_{\eta_*} = \frac{\pi\, St}{b(a-1)}(1-\theta) - \left(\frac{1}{Pe}+\frac{1}{Pe_t}\right)\frac{\frac{\partial\theta}{\partial\eta}\Big|_+ + \frac{\partial\theta}{\partial\eta}\Big|_-}{a-1} \qquad (3)$$

Downstream of the heated part of the layer the radial gradient of the temperature vanishes:

$$\frac{\partial \Theta}{\partial \eta_H} = 0 \qquad (4)$$

To solve Equ. (1) together with the boundary conditions (2), (3) and (4), knowledge about the turbulent Peclet number, Pe_t, is required. According to Prandtl's mixing length hypothesis the mixing coefficient for momentum, A_τ, is related to the mixing length, l, and the velocity gradient. Assuming that the ratio of the mixing coefficient for heat, A_q, to that of momentum A_τ is equal to 2, we find

$$A_q = 2\, l^2\, (du/dr) \qquad (5)$$

The mixing length, l, is set proportional to the tube diameter, d, as the size of the vortices shed from the tubes depends on the tube diameter.

$$l = \Lambda\, d \qquad (6)$$

The velocity gradient in Equ. (5) is assumed to be proportional to the difference between velocity, u_s, at the boundary layer separation ($u_s \approx u_e$) and velocity in the tube rear ($u_r \approx 0$):

$$(du/dr) = c\, (2\, u_e/d) \qquad (7)$$

(6) and (7) in (5) yields

$$A_q/\, (u_e d) = 1/Pe_t = c\, (2\Lambda)^2 \qquad (8)$$

Equ. (8) correlates the turbulent Peclet number with the flow quantity Λ, which is the length scale parameter of the turbulence structure. Its value can experimentally be determined by cross-correlation messurements of the velocity fluctuations. For this purpose the two-probe hot wire anemometry is applied.

If u'_η and $u'_{\eta+\Delta\eta}$ are the velocity fluctuations at the position η and $\eta+\Delta\eta$, respectively, the cross-correlation coefficient $R_{(\eta)}$ is given by

$$R_{(\eta)} = \frac{\overline{u'_\eta \cdot u'_{\eta+\Delta\eta}}}{\sqrt{\overline{u'^2_\eta} \cdot \overline{u'^2_{\eta+\Delta\eta}}}} \qquad (9)$$

Integration of the cross-correlation coefficient $R_{(\eta)}$ along η yields the parameter

$$\Lambda = \int_0^\infty R_{(\eta)}\, d\eta \qquad (10)$$

If Λ has been measured the only unknown quantity is the constant c which must be fitted to the experimental evidence.

3) Cross-correlation measurements

The gas-mixing tests have been conducted in a helical test bundle, sketched in Figure 1. This test body was not accessible to traversing hot wire probes. Therefore the correlation-measurements must be carried out in a separate tube bundle. It was a staggered tube arrangement with transversal pitches of a = 2 and longitudinal pitches of b = 1.4. The tube diameter was d = 0.15 m. The bundle consisted of seven rows.

The hot wire measurements were performed downstream of the fifth row. Four planes were selected as shown in Figure 2. It is evident that the turbulence parameter varies in the whole domain of investigation by a factor of

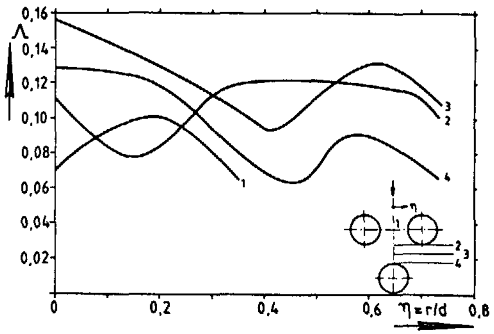

Figure 2
Local distribution of the length scale turbulence parameter in a staggered tube bundle

about two. The lowest values are observed in the narrowest cross section between the tubes, the highest in the central position of the middle plane (3). The latter position, however, just represents the area where the dispersive heat flux normal to the main flow direction occurs. This fact is important for the decision about which average value of Λ is most appropiate. It seems reasonable to chose the mean value of maesured in plane (3). Though being aware of that the effect of variable Λ on the turbulent heat exchange may not be linear an arithmetic average was applied which is about $\Lambda_{av} = 0.12$. The experimental results of the gas mixing tests described below could best be correlated with the theoretical results setting the turbulent Peclet number to a constant value of $Pe_t = 8,2$. From this value the constant, c, occurring in Equ. (8) becomes c = 2.12.

$$1/Pe_t = 2.12\ (2 \times \Lambda)^2 \qquad (11)$$

Each particular curve plotted in Figure 2 represents the mean value of data picked up at different Reynolds numbers. The scattering of the results was within the band width of ± 10 % though varying the Reynolds number by a factor of five. As a consequence the turbulent Peclet number must be independent of the Reynolds number, which is in good agreement with the test results.

4) Solution procedure

Equation (1) is nummerically solved together with the boundary conditions (2), (3) and (4) by a finite differencing method. As the streamwise second order derivation $\partial^2\theta/\partial\xi^2$ is not neglected an implicit iteration procedure is required. The term on the left side of Equ. (1) is written as forward differencing, the right side as central differencing. The iteration converges if the relative step width h/d satisfies the following condition

$$\frac{h}{d} \geq 4\left(\frac{1}{Pe} + \frac{1}{Pe_t}\right) \qquad (12)$$

It is obvious that for Pe > 1000 the quantity 1/Pe is negligibly small compared to $1/Pe_t = 0.12$. Then Equ. (12) yields

$$\frac{h}{d} > \frac{4}{Pe_t} \equiv 8.48\,(2\Lambda)^2 \qquad (13)$$

Equ. (13) demonstrates that the relative step width depends on the square of the turbulence parameter, Λ. Of course, the step width must be larger than the size of the turbulence structure. Equ. (13) satisfies this condition for $\Lambda > 0.0295$.

The heat input from the central tube layer was calculated using the approximation equation given by /1/ for this heat exchanger:

$$Nu\ Pr^{-0.36} = 0.253\ Re^{0.62} \quad (Re < 7.5 \times 10^4)$$
$$Nu\ Pr^{-0.36} = 0.067\ Re^{0.74} \quad (Re > 7.5 \times 10^4) \qquad (14)$$

5) Experimental and theoretical results

Figure 3 illustrates the experimental results together with those of the computation (full lines). The diagram resumes data from experiments at variable Reynolds numbers and for different coolants. The best agreement between theory and experiment could be achieved setting the turbulent Prandtl number to $Pe_t = 8.2$ for the whole Reynolds number range covered. This means physically that the length scale of the turbulence structure does not vary with the Reynolds number. This evidence has already been mentioned above in context with the turbulence measurements.

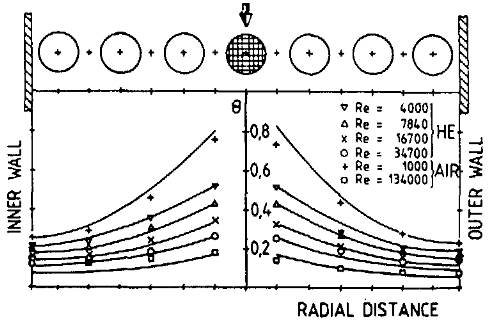

Figure 3
Experimental and theoretical temperature distribution in the gaps of the last row of the helical tube bundle

If the turbulent Peclet number is constant, the solution of Equ. (1) should be independent of the Peclet number, i.e. in our case of the Reynolds number. This quantity, however, occurs as a parameter in Figure 3. The explantion of this apparent discrepancy is that the Reynolds number effect is introduced from the boundary conditions at the heated tube layer. The heat input is not linear with Re, but depends on it according to Equ. (14).

Figure 4 shows the experimental and theoretical temperature distribution 0.4 m downstream of the bundle. The computation has been done using the same above value for the turbulent Peclet number.

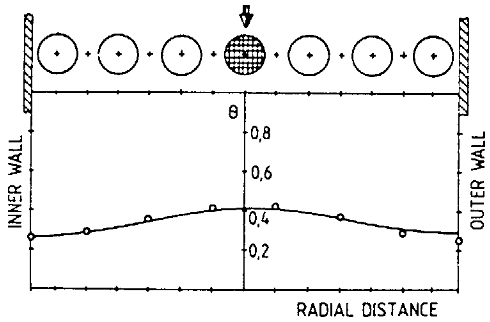

Figure 4
Temperature distribution 0.4 m downstream of the helical tube bundle

6. Comparison between present and previous results

Mixing coefficients for heat exchangers have been measured by the authors (2), (3) and (4). Efferding and Landa /2/ investigated an in-line bundle (a = 1.57; b = 1.44) in the range of Reynolds number $10^4 < Re < 6 \times 10^4$. They evaluated temperature profiles. Gülich /3/ applied a CO_2-tracer technique to a tube bank of nearly the same in-line tube arrangement (a = 1.6; b = 1.42) and varied the Reynolds number from 7×10^3 to $1,5 \times 10^5$. Jones et al. /4/ tested several heat exchanger models of in-line and staggered arrangement in the range of Reynolds number $1.1 \times 10^4 < Re < 6.6 \times 10^4$. In the present paper only their results related to bare tubes are referred. Figure 5 gives the composition of all results together with the present findings. The turbulent Peclet number was found to be independent of Re by Jones et al. and in the present work. Gülich observed a strong variation with Re while Effering measured the steep decrease only for the

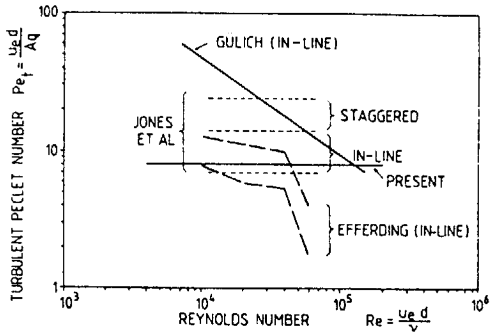

Figure 5
Turbulent Peclet number vs. Reynolds number. Experimental data of several authors.

highest Reynolds number achieved. There was made an attempt to verify our experimental temperature profiles using Gülich's Pe_t-data. At low Reynolds number, of course, the disagreement was considerable.

7) Concluding remarks

Gas mixing experiments have been carried out in the range of Reynolds number $10^3 < Re < 1.35 \times 10^5$. The theoretical and experimental results exhibited best agreement for a constant value of the turbulent Peclet number, $Pe_t = 8.2$. It has been demonstrated that the turbulent Peclet number can be related to a single flow quantity, i.e. the length scale parameter of the turbulence structure. This parameter has experimentally be determined and it was found that its value is independent of the Reynolds number. This evidence is in good agreement with the findings of the gas mixing tests.

Nomenclature

A_q	turbulent exchange coefficient of heat
A_τ	turbulent exchange coefficient of momentum
a	thermal diffusivity

a	transversal pitch
b	longitudinal pitch
c	constant
d	tube diameter
h	step width of the computation grid
l	mixing length
q	heat flux
r	radial coordinate
R	correlation coefficient
Ri, Ro	inner or outer radius of the helical heat exchanger
T	temperature
u	velocity component, x-direction
u'	velocity fluctuation
v	velocity component, v-direction
v'	velocity fluctuation
x	streamwise coordinate
z	number of tube rows

Greek symbols

ε	accuracy threshold
η	dimensionless radial coordinate
Θ	dimensionless temperature
Λ	length scale parameter of the turbulence structure
ν	kinematic viscosity
ξ	dimensionless axial coordinate

Subscripts

av	average
e	narrowest cross section between the tubes
gas	referred to gas
H	referred to the heated tube layer
i	bundle inlet
t	turbulent
w	wall

Characteristic numbers

Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
St	Stanton number

References

/1/ Groehn, H.G.; Experimentelle Untersuchung zur Thermohydraulik des Helium/Helium-Wärmeübertragers in Wendelbauweise, Jahrestagung Kerntechnik München, pp. 117-120, 1985

/2/ Efferding. L.E. and Landa, J.F.; Experiment on gas mixing in a cross-flow tube bundle. Gulf General Atomic-Rep. GAMD-8766, San Diego, USA, Jan. 1969

/3/ Gülich, J.W.; Bestimmung der turbulenten Austauschkoeffizienten in quer angeströmten Rohrbündeln, Wärme- und Stoffübertragung 6, pp. 92-100, 1973

/4/ Jones, R.C., Lis, J. and Massey, T.H.; An experimental investigation of thermal mixing in cross-flow tube banks. Proc. 6 th Int. Heat Transfer Conf., Toronto, vol. 6, pp. 225-260, 1978