PREDICTION OF HEAT TRANSFER COEFFICIENT FOR THERMAL REGENERATORS

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ABSTRACT: *Correlation of heat transfer coefficients for air flow through the regenerator constructed from randomly packed spheres is reported for the symmetric-balanced mode of operation. The experimental results have been correlated by the least square regression and the following correlation has been obtained:*

$$\varepsilon J_h = 0.1783\ Re_m^{-0.2906}$$

The present correlation has been compared with the heat transfer coefficient correlations in the literature.

KEY WORDS: *Thermal regenerator, Heat transfer coefficient, Packed bed, Experimental.*

INTRODUCTION

Regenerative heat exchanger is an apparatus in which the heat to be transferred is stored within the exchanger for a predetermined period of time and then removed. Either the heat absorbing elements must remain stationary and the fluid streams must be alternately directed to it or the elements must be moved back and forth between the passages of the hot and cold fluids. Correspondingly, regenerators may be divided into two types: fixed-bed and rotary. They have been used in industry for many years for a variety of applications: Cryogenic separation processes, air preheating in glass and steel making, in power plants and gas turbines. Only the fixed-bed type is used for this investigation. However, *Shah* [1] has shown that the theory should apply equally to both types.

The cyclic operation of the regenerator results in transient heat transfer such that the matrix and the gas temperatures vary with time and position during a period.

Regenerator operation is usually defined in terms of two dimensionless parameters: the dimensionless length, Λ, and the utilization factor, U:

$$\Lambda = \frac{h\,A\,L}{G\,C_g} \quad (1)$$

$$U = \frac{G\,C_g\,P}{\rho b_s\,C_s\,L} \quad (2)$$

These two parameters have been taken directly

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from the two differential equations of the simplest mathematical model of the regenerator [2]. *Hausen* [3] defined two dimensionless parameters for the regenerator as Λ and π, where π is:

$$\pi = \frac{h\,A\,P}{\rho b_s\,C_s} \tag{3}$$

therefore:

$$U = \frac{\pi}{\Lambda} \tag{4}$$

The thermal operating characteristics are reflected by the effectiveness and the outlet fluid temperature swings. These are defined for the hot and cold periods as:

$$\eta_h = \frac{(G\,C_g\,P)_h(t_{hi} - \bar{t}_{ho})}{(G\,C_g\,P)_{min}(t_{hi} - t_{ci})} \tag{5}$$

$$\eta_c = \frac{(G\,C_g\,P)_c(\bar{t}_{co} - t_{ci})}{(G\,C_g\,P)_{min}(t_{hi} - t_{ci})} \tag{6}$$

$$\delta t_h = \frac{t_{ho,max} - t_{ho,min}}{t_{hi} - t_{ci}} \tag{7}$$

$$\delta t_c = \frac{t_{co,max} - t_{co,min}}{t_{hi} - t_{ci}} \tag{8}$$

For the fundamental and simplest mathematical model of the regenerator which assumes the mechanism of heat transfer to be solely convective, the hot and cold effectiveness and the outlet fluid temperature swings are a function of four dimensionless parameters as follows:

$$\eta_h, \eta_c, \delta t_h, \delta t_c = f(\Lambda_{min}, \Lambda_{max}, U_{min}, U_{max}) \tag{9}$$

Where U_{min} and U_{max} are minimum and maximum of the U values for the hot and cold streams. Λ_{min} and Λ_{max} are related to the U_{min} and U_{max}. By defining the asymmetry and unbalanced factors as:

$$\gamma = \frac{\Lambda_{min}}{\Lambda_{max}} \tag{10}$$

$$\beta = \frac{U_{min}}{U_{max}} \tag{11}$$

Therefore, the effectiveness and the outlet fluid temperature swings may be a function of rearranged parameters as follows:

$$\eta_h, \eta_c, \delta t_h, \delta t_c = f(\Lambda_{min}, \gamma, U_{min}, \beta) \tag{12}$$

Based on the foregoing parameters, regenerators can be classified in four categories as follows:

symmetric-balanced	$\gamma = 1, \beta = 1$
asymmetric-balanced	$\gamma \neq 1, \beta = 1$
symmetric-unbalanced	$\gamma = 1, \beta \neq 1$
asymmetric-unbalanced	$\gamma \neq 1, \beta \neq 1$

In the symmetrical and balanced case where $\gamma = 1$ and $\beta = 1$, so that $\Lambda_{min} = \Lambda_{max}$ and $U_{min} = U_{max}$, therefore, the effectiveness and outlet fluid temperature swings are a function of two dimensionless parameters Λ and U. Although the symmetric-balanced case is very rarely encountered in a practical situation, but it has been used by experimentalists to predict the heat transfer coefficient which of course would be applicable for the analysis of the other modes of operation. *Hollins* [4] solved the partial differential equations of the simplest Nusselt (III) model [5] by finite difference techniques and produced curves of constant Λ on η-U coordinates for the symmetric-balanced case.

Hence, for any experimental run, from the operational conditions and the physical properties of the fluid and the solid the values of U will be known. The values of experimental hot and cold effectiveness also can be evaluated from inlet and outlet temperature measurements using Eqs. 5 and 6. This enables the values of Λ to be calculated, and since $h = GC_g\Lambda/AL$, therefore, the heat transfer coefficient can be evaluated. This approach is used initially for the analysis of the experimental data in the present investigation to predict the heat transfer coefficients for all modes of operation in the regenerator. For the asymmetric mode of operation, where $\Lambda_{min} \neq \Lambda_{max}$, the analysis is more complex, since there are two different values of heat transfer coefficients for the hot and cold fluid streams. In this case the heat transfer correlation from the symmetric-balanced results is used to predict the first values of hot and cold Λ's. This allows the symmetry factor (γ) to be calculated. For the iteration only one of the Λ's is incremented while the other value is kept constant.

The effectiveness is then simulated for each loop by the numerical solution of the model and is compared with the experimental effectiveness until the predetermined limit is reached.

EXPERIMENTAL

Apparatus

The schematic diagram of the apparatus is shown in Fig. 1. Air from the compressor passes through an air filter and a feed back pilot operated regulator which controls the flow rate. A bank of three heaters (H1-H3), provides a smooth temperature. The direction of gas flow through the bed is controlled by four solenoid valves (SV1-SV4). For the hot period SV2 and SV4 are open while other two are closed. In the cold period SV1 and SV3 are open but the rest are closed and therefore the flow is directed in the counterflow through the regenerator. The bed was packed by pouring the particles into the section which was continuously tamped. They were supported between two 8-mesh steel gauze disks, which were located by three small lugs. The rig was insulated internally and externally with 3 mm flexible expanded rubber and 30 mm fiber glass blanket respectively. The internal insulation minimizes the heat loss and eliminates the excess voidage at the wall. For the symmetric-balanced case the same flow rate will be used in each period, while for the asymmetric and/or unbalanced case a fifth solenoid valve, SV5 will be used to alter the flow rate through the bed. The input temperature rise for the bed is produced by heater H4. To avoid changing physical properties of the fluid, this rise never exceeds more than 10 °C. The gas temperatures are continuously monitored at the certain points using the 99.99% platinum resistance thermometers. The recorded hot and cold temperatures from the bed are used to calculate the thermal ratios as:

$$\Phi_h = \frac{t_{hi} - \bar{t}_{ho}}{t_{hi} - t_{ci}} \quad (13)$$

$$\Phi_c = \frac{\bar{t}_{co} - t_{ci}}{t_{hi} - t_{ci}} \quad (14)$$

When these values are repeated for two subsequent cycles within a predetermined limit the cyclic steady-state is achieved. For unbalanced operation, the thermal ratios are converted to effectiveness values using Eqs. 5 and 6.

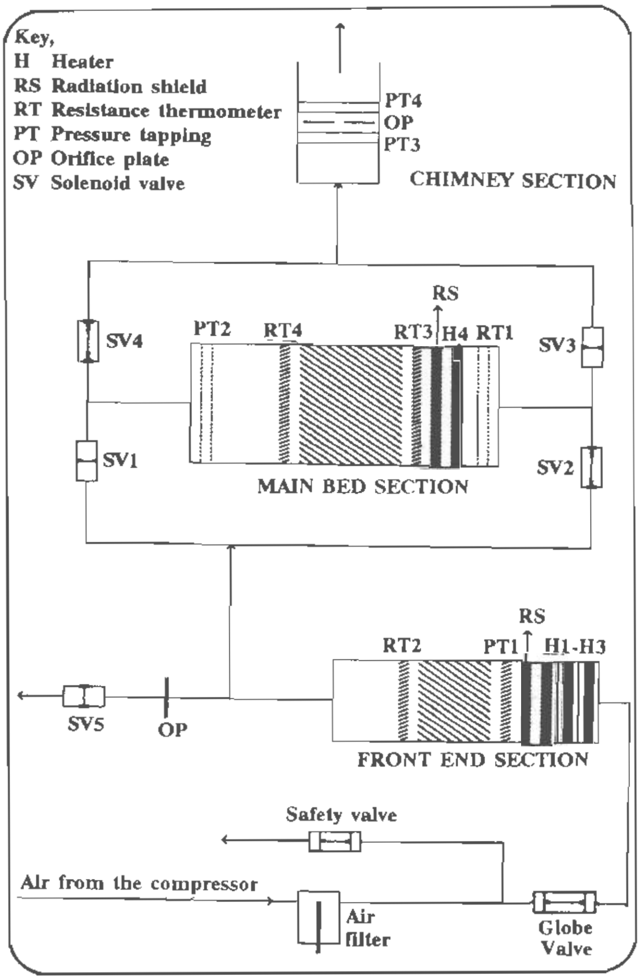

Fig. 1: Schematic diagram of the experimental apparatus

The microcomputer is the S-100 based Hotel Microsystems (HMS) Minstrel which is connected to the apparatus to monitor, log data, and control the operating conditions. The experimental control programs have been written in "C" language to be compatible with the system. In the symmetric-balanced operation the regenerator is run with the fixed flow rate for both periods, which are of identical duration, until cyclic equilibrium is reached, while for the asymmetric and/or unbalanced case one of the flow rates or period times may be altered. The values of the effectiveness are calculated at the end of each cycle from the time averaged inlet and outlet temperatures. Cyclic equilibrium is taken to have been reached when the effectiveness values of successive cycles differ by less than some small values. The mean flow rates, room temperature and the temperature of the gas passing through the orifice plate are also required for each period. On reaching equilibrium a further cycle is completed in which the tempepeature profiles throughout the apparatus are recorded.

Procedure

A series of 25 counter current flow regenerator experiments have been conducted over the range $1.0<G<3.4$ kg/m^2 s in symmetric-balanced mode of operation for a bed randomly packed with 1/4" alumina spheres. The apparatus was operated at six different flow rates and up to five different period, for each flow rate. Each experiment is identified by a unique combination of characters (e.g., SB1. G5. 120). The first character specifies the operation types of the experiment e.g., symmetric-balanced case and the bed under consideration. The second set of characters gives an indication of the flow rate used, viz,

$G1\cong3.177$ $G2\cong2.596$ $G3\cong2.121$ $G4\cong1.617$ $G5\cong1.068$ kg/m^2 s

The final number specifies the period length in seconds. The physical properties and bed assemblies are listed in Table 1.

Table 1: Bed and packing physical properties

Particles:	
Diameter, m	0.00655
Mass, kg	1.344
Density, kg/m3	3630.0
Thermal conductivity, W/m K	1.2
Specific heat capacity, J/kg K	790.17
Bed:	
Voidage	0.395
Diameter, m	0.0693
Length, m	0.1610
Area per unit volume, 1/m	554.5

The procedure for the analysis of the experimental data is shown in Fig. 2. An iteration technique has been applied to evaluate Λ values from experimental values of effectiveness and utilization factors. An arithmetic average values of the hot and cold effectiveness has been calculated as:

$$\eta_{exp} = \frac{\eta_{exp,h} + \eta_{exp,c}}{2} \tag{15}$$

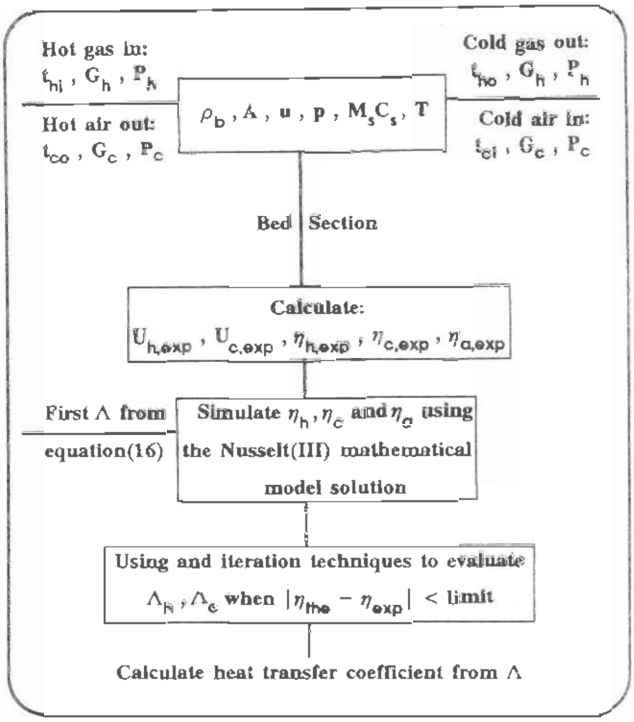

Fig. 2: Summary of the experimental data analysis program

The first value of Λ may be obtained from [6] as:

$$\Lambda_{min} = \frac{2\eta_{exp}}{1 - \eta_{exp}} \tag{16}$$

This value then will be incremented and used in conjunction with the experimental values of U to evaluated the effectiveness by the Nusselt (III) mathematical model solution. The evaluated effectiveness then will be compared with the experimental value until they match to a predetermined limit. From Λ then the heat transfer coefficient is determined by:

$$h = \frac{G\,C_g\,\Lambda}{A\,L} \tag{17}$$

Heat transfer correlations

Heat transfer results in packed-beds and regenerators are normally represented in the forms of Nu, PJ_h, and Stanton number, while the flow parameter is a special form of the Reynolds number. *Burns* [7] interpreted the experimental data by the Nusselt (III) model and correlated the heat transfer coefficients for the mild-steel spheres of two sizes 6.35 mm and 3.175 mm. His correlation for the counter current symmetric-balanced regenerator is:

$$\varepsilon J_h = 0.1512\ Re_m^{-0.2595} \quad (18)$$

Heggs [8] tested spheres of different sizes and materials and found the following correlation for the single-blow experimental data:

$$\varepsilon J_h = 0.2550\ Re_m^{-0.3350} \quad (19)$$

An extensive review of the literature on heat transfer between fluids and particles has been reported by *Barker* [9] from which two correlations of *Dabora* et al. [10] and *Lancashire* et al. [11] are for the regenerative systems. The results of *Dabora* [10] for the regenerative heat exchanger, using the alumina pebbles at 2000 °F, can be represented in the following correlation:

$$\varepsilon J_h = 0.1360\ Re_m^{-0.2980} \quad \text{at } 2200<Re<3700 \quad (20)$$

RESULTS AND CONCLUSIONS

The experimental results of the present work have been correlated in the form of:

$$\varepsilon J_h = C_1\ Re_m^{C2} \quad (21)$$

The mean values for each flow rate have been fitted by least squares regression and the following correlation have been obtained:

$$\varepsilon J_h = 0.1783\ Re_m^{-0.2906} \quad (22)$$

with 99.6% correlation coefficient and 25 degrees of freedom.

The experimental measurement of effectiveness, utilization factor, evaluated Λ and heat transfer coefficients which have been analyzed by the simplest Nusselt (III) model are listed in Table 2 for the symmetric-balanced mode of operation. The theory of the Nusselt (III) model assumes that no heat is transferred from the bed to the surrounding and on reverse, however the discrepancies between the hot and cold effectiveness show that heat losses exist during the experiments. $\Delta\eta$ values from Table 2 suggest that heat loss is increased when the flow rate is decreased. Theory predicts that the effectiveness decreases when period time increases for a constant flow rate. The relationship between η and P are illustrated in Fig. 3. It is apparent from the curves that the periodicity effect on the effectiveness increases when the flow rate decreases. The theory also suggests that the heat transfer coefficients and thus the Λ's should remain constant for the same flow rate, however, the evaluated values of Λ and therefore, the heat transfer coefficients for each flow rate vary with period, but this never exceeds 4% which may be due to the experimental errors. The comparison between the present results and the correlations obtained by *Burns* [7] and *Heggs* [8] illustrated in Fig. 4 shows that Burns's correlation is very similar to the present work which is to be expected. However, Heggs's correlation for the packed beds predict higher values of heat transfer coefficients. This may be due to the fact that in packed beds the solids have much more time to be saturated by the fluid temperature than in the cyclic regenerators.

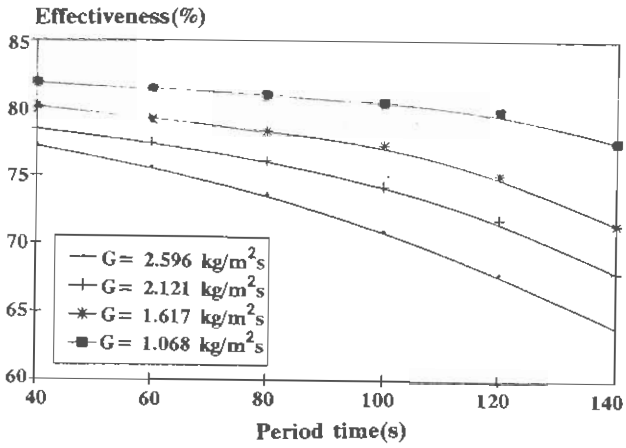

Fig. 3: Periodicity effects on the effectiveness

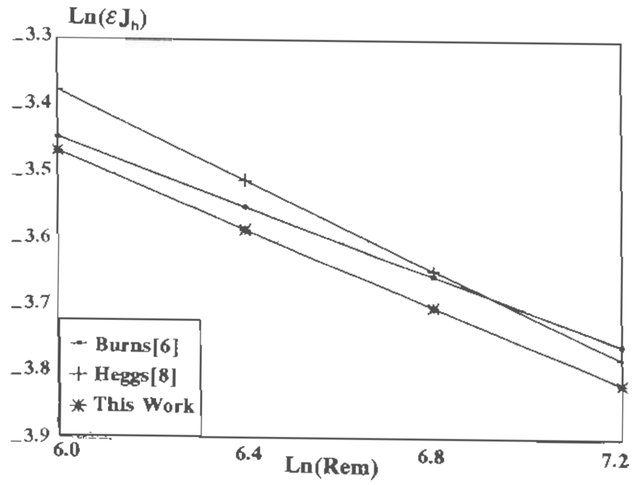

Fig. 4: Comparison of the heat transfer results

Table 2: Experimental results of the symmetric-balanced runs

Run	$\eta_{a,exp}$%	$\Delta\eta$%	U_{exp}	Λ	h (W/m^2 K)	Ln Re_m	Ln εJ_h
	G_a = 3.177 kg/m^2 s						
SB2.G1.20	77.00	0.3	0.228	6.89	246.40	7.107	-3.722
SB2.G1.40	75.69	0.9	0.456	6.94	247.80	7.106	-3.715
SB2.G1.60	73.26	2.0	0.686	6.87	245.93	7.108	-3.724
SB2.G1.100	66.39	4.1	1.145	6.98	250.38	7.110	-3.708
	G_a = 2.596 kg/m^2 s						
SB2.G2.40	77.21	0.2	0.373	7.32	214.06	6.907	-3.661
SB2.G2.60	75.67	0.4	0.560	7.33	214.33	6.906	-3.660
SB2.G2.100	73.56	1.7	0.747	7.34	214.60	6.906	-3.658
SB2.G2.100	70.92	2.0	0.933	7.40	216.13	6.906	-3.651
SB2.G2.120	67.78	2.1	1.120	7.50	219.06	6.906	-3.638
	G_a = 2.121 kg/m^2 s						
SB2.G3.40	78.46	1.8	0.305	7.70	183.66	6.704	-3.611
SB2.G3.60	77.52	0.2	0.457	7.76	185.04	6.702	-3.603
SB2.G3.80	76.15	0.6	0.610	7.81	186.50	6.704	-3.597
SB2.G3.100	74.24	0.3	0.763	7.78	185.86	6.703	-3.600
SB2.G3.120	71.91	1.3	0.916	7.76	185.38	6.705	-3.603
SB2.G3.180	63.89	0.4	1.373	8.66	206.94	6.705	-3.493
	G_a = 1.617 kg/m^2 s						
SB2.G4.40	80.15	3.8	0.233	8.37	152.39	6.433	-3.528
SB2.G4.60	79.32	1.9	0.349	8.27	150.68	6.433	-3.539
SB2.G4.80	78.36	1.9	0.465	8.23	149.87	6.433	-3.544
SB2.G4.100	77.33	2.3	0.582	8.27	150.58	6.433	-3.539
SB2.G4.120	75.90	2.1	0.698	8.22	149.68	6.433	-3.545
SB2.G4.180	70.75	4.5	1.047	8.46	154.00	6.433	-3.517
	G_a = 1.068 kg/m^2 s						
SB2.G5.20	81.80	5.0	0.077	9.02	108.45	6.013	-3.453
SB2.G5.40	81.88	6.2	0.153	9.19	109.92	6.012	-3.434
SB2.G5.60	81.48	5.5	0.229	9.13	109.10	6.012	-3.441
SB2.G5.80	81.08	4.7	0.306	9.14	109.47	6.014	-3.439
SB2.G5.100	80.49	6.3	0.381	9.08	108.39	6.010	-3.446
SB2.G5.120	79.82	5.2	0.457	9.04	107.79	6.009	-3.451
SB2.G5.180	77.60	5.7	0.687	9.16	109.48	6.012	-3.437

Nomenclature

- A heat transfer area per unit volume of the bed, 1/m
- C specific heat capacity, J/kg K
- C_1,C_2 constant parameters in Eq. 21
- d packing diameter, m
- G superficial mass velocity, kg/m^2 s
- h convective heat transfer coefficient, W/m^2 K
- J_h Colburn j factor
- L length of the bed, m
- M mass of the solid, kg
- ε bed voidage
- P gas period
- Re_m modified Reynolds number, $2Gd/3\mu(1-\varepsilon)$
- Re Reynolds number, Gd/μ
- t gas temperature, K

U utilization factor
u velocity, m/s
T solid temperature, K

Greek letters

ρ density, kg/m^3
ρb bulk density, kg/m^3
η effectiveness
Λ reduced length
π reduced period
δt outlet gas temperature swing
Φ thermal ratio
μ viscosity, kg/m s
γ asymmetry factor
β unbalanced factor

Subscripts

a average
c cold period
exp experimental
g gas phase
h hot period
i input
o output
max maximum
min minimum
s solid phase

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REFERENCES

[1] Shah, R. K., "*Thermal Design Theory for Regenerators*", in *Heat Exchangers Thermal-Hydrauiic Fundamentals and Design*, Edited by Kakac, S., Bergles, A. E. and Mayinger, F., 721-763(1982).

[2] Sadrameli, M., *Investigation of Asymmetric and Unbalanced Regenerators,* Ph.D. Thesis, University of Leeds(1988).

[3] Hausen, H., *Heat Transfer in Counter Flow, Parallel Flow and Cross Flow,* McGraw-Hill, New-York (1983).

[4] Hollins, S. J., *Development of an Apparatus to Investigate the Characteristics of Regenerative Heat Exchangers,* Ph.D. Thesis, University of Leeds (1981).

[5] Nusselt, W., *Die Theorie des Winderhi-tzers,* V.D.I., **71,** 85(1927).

[6] Heggs, P. J. and Sadrameli, M., "*Effectiveness Charts for the Operation of Counter Current Regenerators*", Heat Transfer, Vol. 2, 2nd U.K. National Heat Transfer Conference, Glasgow (1988).

[7] Burns, D. A., "*Practical and Theoretical Investigation of Thermal Regenerator Operation,* Ph.D. Thesis, University of Leeds(1986).

[8] Heggs, P. J., *Transfer Processes in Packings Used in Thermal Regenerators,* Ph.D Thesis, University of Leeds(1967).

[9] Barker, J. J., *Heat Transfer in Packed-Beds, Ind. Eng. Chem.,* **57,** No. 4, 43, April(1965).

[10] Dabora, E. K. et al., "*Description and Exsperimental Results of Two Regenerative Heat Exchangers*", AFORS Contract No. AF18(1600) 1199, University of Michigan, TN-58-226, Feb. (1958).

[11] Lancashire, B., Lezberg, E. A. and Morris, J. F., "*Experimental Results of a Heat-Transfer Study from a Full Scale Pebble-Bed Heater,* NASA pub. E-724.