CONF-830841--5

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--83-2351

DE83 017320

TITLE: EXPERIMENT TO DETERMINE PROPERTIES OF PACKED PARTICLE BEDS AND REGENERATORS AT CRYOGENIC TEMPERATURES

AUTHOR(S): J. A. Barclay, W. C. Overton, Jr., W. F. Stewart, and S. Sarangi

SUBMITTED TO: 1983 Cryogenic Engineering Conference, Colorado Springs, CO
Also to be published in the Advances in Cryogenic Engineering
Plenum Publishing Company, New York



Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MASTER

# EXPERIMENT TO DETERMINE PROPERTIES OF PACKED PARTICLE BEDS AND REGENERATORS AT CRYOGENIC TEMPERATURES*

J. A. Barclay, W. C. Overton, Jr., W. F. Stewart, and Sunil Sarangi#

Los Alamos National Laboratory, Los Alamos, NM 87545

## INTRODUCTION

The testing of the properties of packed-particle beds and regenerators at cryogenic temperatures as low as 4 K is an essential part of the magnetic refrigeration research and development program at the Los Alamos National Laboratory. We envision magnetic refrigeration and heat pump systems operating in various ranges from 4 K to ambient temperature and above. Only pressurized helium gas appears suitable as the heat exchange fluid for the low-temperature applications. Because published data on the properties of porous beds at low temperatures is sparse, we have found it necessary to develop an experimental test apparatus to study the properties of various configurations of beds and regenerators. Two of the well-known methods for such studies are the steady-enthalpy-flux method[1] and the single-blow transient method.[2] We have developed an experimental system in which gas flow can be suddenly switched to an alternate hotter (or colder) flow in step-function fashion at temperatures from 4 to 300 K. This apparatus will yield information on steady-state heat transfer and friction factors as well as on the transient behavior. Such information is very important to the design of high-efficiency magnetic refrigeration systems.

This paper describes this experimental apparatus and presents the results and analysis of recent measurements on packed-particle beds in the liquid helium and liquid nitrogen temperature ranges.

---

#On leave from the Indian Institute of Technology, Kharagpur 721 302, India

*Work performed under the auspices of the U. S. Department of Energy with support from DARPA and NASA/KSC.

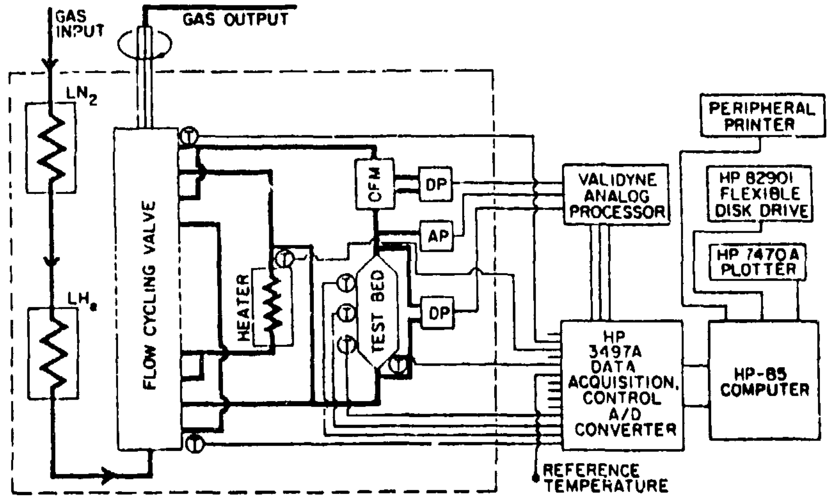


Fig. 1. Schematic of apparatus and data acquisition system. Portions enclosed by dashed lines are inside a large dewar. The gas flow rate is measured by an external flow meter at gas output.

EXPERIMENTAL

The key to the operation of the experimental system, shown schematically in Fig. 1, is the flow cycling valve. This is a precision-machined valve[3] that allows switching and/or blocking of the gas stream flow even at liquid helium temperatures in accordance with the various cycles of operation depicted in Fig. 2. The valve can be operated manually by rotating a control shaft which extends out of the dewar. Switching times are of the order of 1/2 to 1 s. Pressurized helium gas enters the system, as shown in Fig. 1, at a rate determined by the setting of a control valve at gas output. The gas is cooled initially to $LN_2$ temperature by the heat exchanger indicated. It may be further cooled to 4 K by heat exchange in the LHe pot. Temperatures above 4 K can be achieved by switching the gas flow through the heater.

The cold gas enters the cycling valve, as shown in Fig. 2 (A). In position (A), the gas temperature, pressure, and flow rate can be set as required. Switching to position (B) of Fig. 2, one can bring the test bed to thermal equilibrium at gas-stream flow temperature. In position (C), cold gas input flows through a 1000-W heater bed. In this position the gas flow is 10 K to 20 K hotter than the input gas, where, again the flow variables can be set as required. In position (D) the hotter gas can be diverted through the test bed.

In order to get a hot-to-cold step function through the test bed, one sets pressures and flow rates by using positions (A), (C), and (D). In position (D) the test bed comes to equilibrium at the hotter gas temperature, pressure and flow rate. The sudden switching to position (B) takes about 1 s but the gas flow rate remains practically constant.

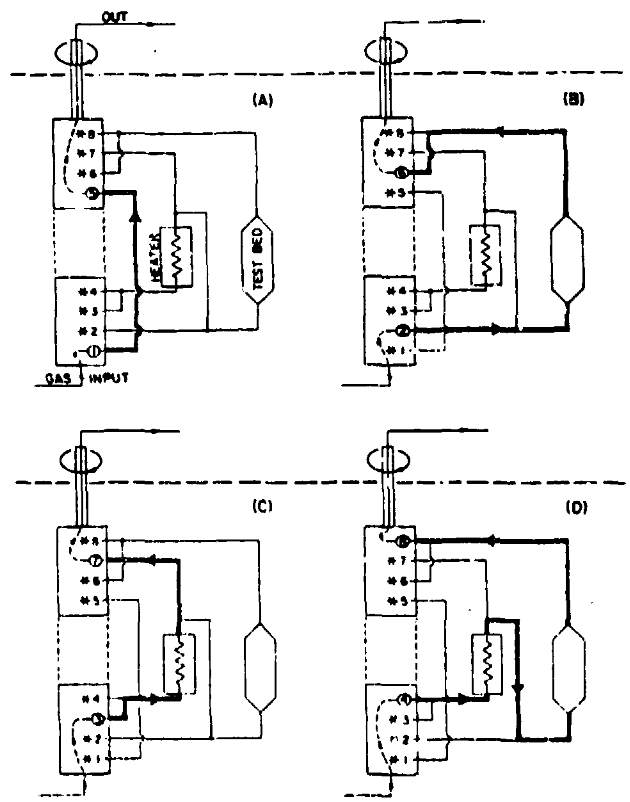


Fig. 2. Schematic showing various modes of gas flow through the cycling valve, heater, and test bed.

The response of the test bed to this temperature step function is recorded automatically by the computer system indicated in Fig. 1. This system measures practically simultaneously the temperatures of all the Au-.07% Fe-chromel sensors shown in Fig. 3. At a chosen time, these thermocouples are switched by the reed-relay and A/D system of the HP-3497 data acquisition electronics so that 11 thermocouples are read in about 1/2 s. We chose to repeat the measurement of the whole set every 6 s. These data were then stored in the memory of the HP 87XM computer and were available for later analysis or output to a printer as desired.

The thermocouple locations in the test bed are described in cylindrical coordinates (r,z), where r = 0 is the center, r = a is the inside radius, z = 0 is the left-most bed screen of Fig. 3, and z = L is the right-most screen. Points z = -L/4 and + 5 L/4 are in the free gas stream. Thermocouples are at (0,-L/4), (0,L/4), (0,L/2), (a/2, L/2), (0,3L/4), (0,5L/4), (a,L/2), and (a+t,L/2). It was hoped that these last two would show a temperature difference between the inside and outside wall of the container. This was not realized on the first runs because thermocouple leads for the (a+t,L/2) position broke. The conical shape at the input and output of the bed was selected in the

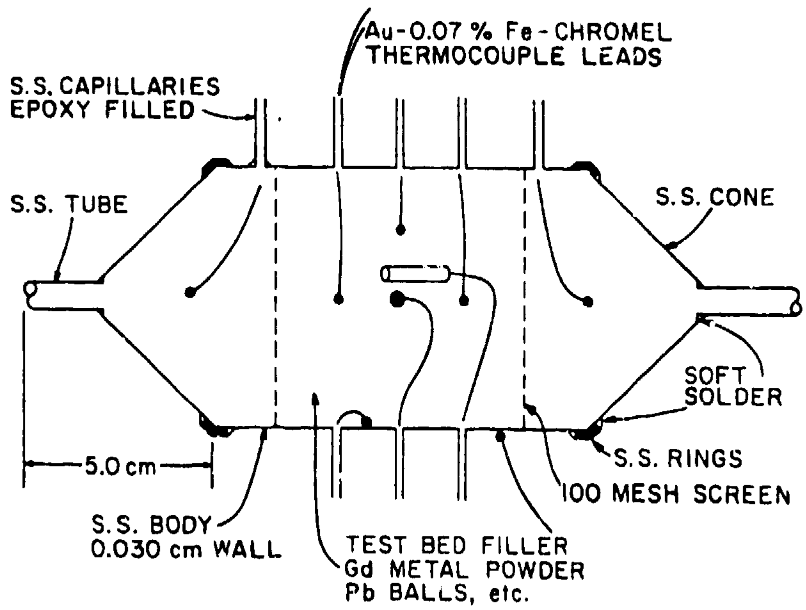


Fig. 3. Schematic of typical test bed showing thermocouple positions. Length L between screens = 4.9 cm, wall thickness t = 0.03 cm and inner radius a = 2.67 cm. Input gas stream enters at the left.

belief that the gas stream flows over the input and output screens would be uniform over the cross sectional area.

We note in Fig. 1 the pressure gauges DP (differential pressure across bed), AP (absolute pressure at bed output), and DP (differential pressure) across the OFM (orifice flow meter). These gauges are of the variable reluctance type and show good characteristics at room temperature. However, the calibration was not consistent at low temperatures. These were then moved to a room-temperature position, which necessitated long connecting tubes from the low-temperature region near the bottom of the dewar. Due to the associated uncertainties in the DP gauge readings, we will not report here our attempts to fit initial friction factor data to an x-y type of Ergun equation.[4] We need only to mention that our y-values, which contain the measured $\Delta p$ across the DP gauge, were inordinately large. However, our Reynolds number calculations are based on flow velocities measured by a well-calibrated flow meter at the point indicated by "gas output" in Fig. 1. Accordingly, the Re values are believed to be accurate.

## EXPERIMENTAL RESULTS AND ANALYSIS

Measurements of the response of the bed to a gas-flow thermal step function permit the calculation of transient heat transfer rates at different positions in the bed. We show in Fig. 4 the response of a test bed made of 1.9-mm diam. lead balls in the liquid $N_2$-temperature range. The hot-to-cold "step function" of Fig. 4 was obtained by adjusting the heater bed output to 90 K and then allowing

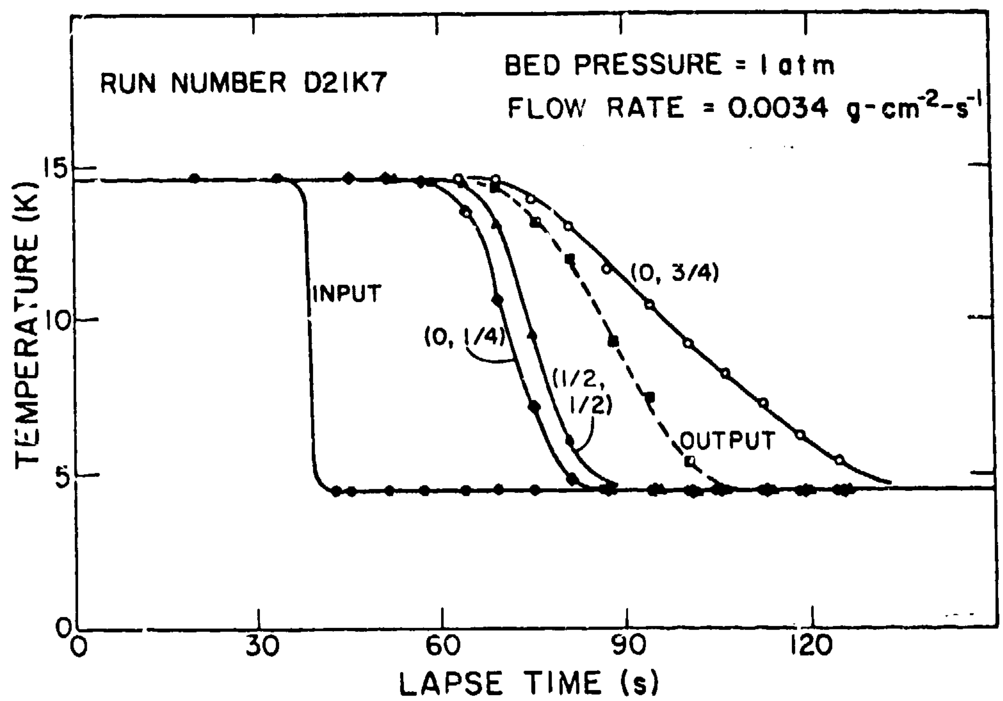


Fig. 4. Response of lead-ball test bed to hot-to-cold step function. Thermocouple locations input at (0,-L/4), in bed, and output at (0, 5L/4) are described in text. The helium flow gas pressure was 3.0 atm.

the whole bed to come to approximate equilibrium at 90 K at a flow rate of 0.11 $g\text{-}s^{-1}\text{-}cm^{-2}$ (i.e., the total flow rate in the screen area of 22.37 $cm^2$ times this value or 0.25 $g\text{-}s^{-1}$ through the whole bed). The cycling valve was then switched from position (D) to position (B) in about 1 s, allowing cold gas at 75.5 K to be introduced into the bed. Note in Fig. 4 that the measured input temperature dropped 10 K from 88 K to 78 K in only about 5 s. This is as close to a step function as we could obtain in this temperature range. In the 4 K to 20 K range, switching times were somewhat faster.

Figure 5 shows the response to switching from 97 K to 77 K, and in Fig. 6 we see the corresponding response to switching from 14.5 K to 4.5 K. It is surprising that the temperature at (0.5L/4) drops before that at (0,3L/4), which does not occur in the cases shown in Figs. 4 and 5. We believe this arises from enhanced peripheral stream velocity due to the greatly decreased viscosity of the He gas at these low temperatures.

The temperature versus time curves at different locations were analyzed to determine the heat transfer coefficients. The procedure is essentially the same as the maximum slope method of Locke[5] except that

(a) The effects of (i) longitudinal conduction, (ii) gas disper-

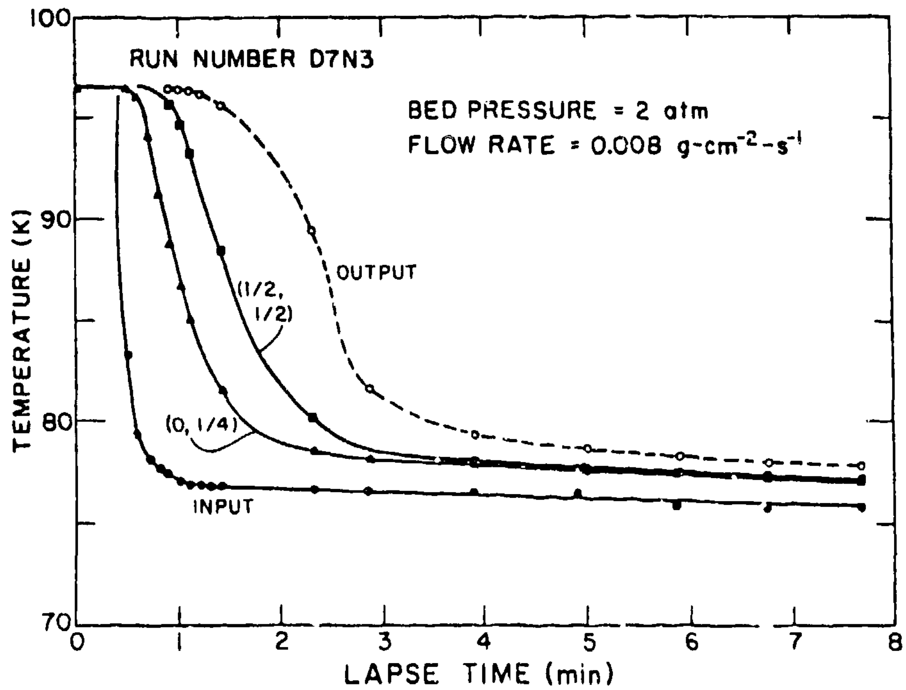


Fig. 5. Response of the lead-ball bed to a hot-to-cold step function in the 97 K-to-75 K temperature range at a pressure of 2.0 atm.

sion and (iii) temperature-dependent matrix specific heat have been considered in deriving the theoretical curves, and

(b) Comparison of the theoretical and experimental profiles were based on an average slope over $0.2 \leq \Theta_g \leq 0.8$ instead of the maximum slope.

It has been shown[6] that the average slope method overcomes some of the shortcomings of the maximum slope method and may be used with larger grid size.

The theoretical curves are computed by solving the following governing equations:

$$\frac{\partial \Theta_g}{\partial y} - \Lambda \lambda_g \frac{\partial^2 \Theta_g}{\partial y^2} + \Theta_g = \Theta_s \tag{1}$$

$$\alpha \frac{\partial \Theta_s}{\partial \tau} - \Lambda \lambda_s \frac{\partial^2 \Theta_s}{\partial y^2} + \Theta_s = \Theta_g \tag{2}$$

with boundary conditions

$$\Theta_s = 0 \text{ at } \tau = 0 \ ; \quad \Theta_g = 1 \text{ at } y = 0. \tag{3}$$

In the above, $\Theta$ = dimensionless temperature = $(T - T_0)/(T_1 - T_0)$ ,

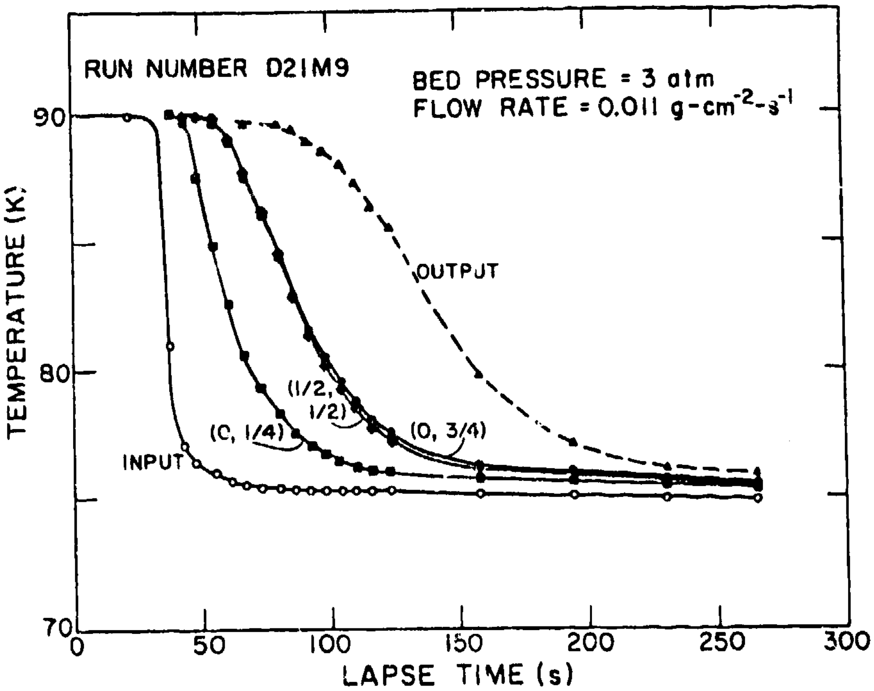


Fig. 6. Response of the lead-ball bed to a hot-to-cold step function in the 15 K to 4 K temperature range at a pressure of 1 atm.

$y$ = dimensionless length coordinate = $(h\ A\ x)/(G\ C_p)$ ,
$\tau$ = dimensionless time = $(h\ A\ t)/[\rho_s\ \bar{C}_s(1 - f)]$ ,
$\Lambda$ = $(h\ A\ L)/(G\ C_p)$ ; $\lambda_s = k_{se}/(G\ C_p\ L)$ ,
$\lambda_g = k_{ge}/(G\ C_p\ L)$ and $\alpha = C_s/C_s$ .

Thermal conductivities $k_{se}$ and $k_{ge}$ are effective values for matrix and fluid, respectively; $C_s$ is the solid specific heat while $\bar{C}$ is a local average value: $\rho_s$ = solid density; $C_p$ = gas specific heat; A = effective area; h = heat transfer coefficient; and G = mass flow rate.

These equations are solved on the HP-87 XM computer using the centered difference approach[7] and the dimensionless gas temperature $\Theta_g$ is determined as a function of dimensionless length y and time $\tau$. The average slope $\Delta\Theta_g/\Delta(\tau/y)$ over the interval $0.2 \leq \Theta_g \leq 0.8$ for various values of y are computed and stored. It may be observed that

$\tau/y = (t/x)\ (G\ C_p)/[\rho_s\ C_s(1 - f)]$

does not contain the heat transfer coefficient h. Hence the observed $\Delta\Theta_g/\Delta(\tau/y)$ for $0.2 \leq \Theta_g \leq 0.8$ may be computed explicitly, which, on comparison with theoretical results, yields[4] the value of y and hence h. The heat transfer coefficient h is related to the Stanton number St according to $St = h/(G\ C_p)$.

It may be observed that our values differ significantly from the correlation given in Ref. 8 (i.e., $St = 0.23\ Re^{-0.3}\ Pr^{-2/3}$), and do

Table 1. Reynolds and Stanton numbers for data of Figs. 4–6.

| Run Number | Temp. Range (K) Matrix Initial | Gas Entry | Location $\frac{r}{a}$ | , $\frac{x}{L}$ | Re[a] | St | St (Ref. 8) |
|---|---|---|---|---|---|---|---|
| D21M9 | 90 | 75 | 0 | 1/4 | 20.4 | 0.085 | 0.119 |
| | | | 1/2 | 1/2 | | 0.091 | |
| | | | 0 | 3/4 | | 0.130 | |
| | | | 0 | 1 | | 0.082 | |
| D7N3 | 97 | 76 | 0 | 1/4 | 14.1 | 0.070 | 0.133 |
| | | | 1/2 | 1/2 | | 0.084 | |
| | | | 0 | 1 | | 0.143 | |
| D21K7 | 15 | 4.5 | 0 | 1/4 | 26.0 | 0.098 | 0.107 |
| | | | 1/2 | 1/2 | | 0.113 | |
| | | | 0 | 3/4 | | 0.027 | |
| | | | 0 | 1 | | 0.055 | |

[a]Re is based on hydraulic diameter and interstitial fluid velocity.[8]

not in themselves show any systematic behavior. This is probably due to the flow channeling in the bed and non-uniform flow in the randomly packed bed. Also, in the liquid helium range, some effects may be attributed to the extremely low viscosity of the cold helium gas flow. We intend to carry out a systematic investigation of the problem of flow distribution in randomly packed beds and the resulting effects on heat transfer, especially at cryogenic temperatures.

References:


1. J. C. Kim and E. B. Qvale, 1970, Analytical and experimental studies of compact heat exchangers, Advances in Cryogenic Engng., 16:302.
2. C. C. Furnas, 1930, Heat transfer from a gas stream to a bed of broken solids, Am. Inst. of Chem. Engng., Trans. Vol. XXIV:142.
3. The first model cycling valve was made by J. E. Dyson, Los Alamos National Laboratory, Los Alamos, New Mexico.
4. S. Ergun, 1952, Mass transfer rate in packed columns: its analogy to pressure loss, Chem. Engng. Progress, 48:227.
5. G. L. Locke, 1950, Heat transfer and flow characteristics in porous solids, TR No. 10, Dept. of Mech. Engng., Stanford University.
6. G. F. Kohlmayr, 1966, Exact maximum slopes for transient matrix heat transfer testing, Int. J. Heat Mass Transfer, 9: 671.
7. D. U. von Rosenberg, 1969, "Methods of Numerical Solutions of Partial Differential Equations," American Elsivier, New York.
8. W. M. Kays and A. L. London, 1964, "Compact Heat Exchangers," McGraw Hill, New York.