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FLUIDIZED BED REGENERATORS FOR BRAYTON CYCLES

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SUMMARY

A recuperator consisting of two fluidized bed regenerators with circulating solid particles is considered for use in a Brayton cycle. These fluidized beds offer the possibility of high temperature operation if ceramic particles are used.

Calculations of the efficiency and size of fluidized bed regenerators for typical values of operating parameters have been made and compared to a shell and tube recuperator. The calculations indicate that the fluidized beds will be more compact than the shell and tube as well as offering a high temperature operating capability.

INTRODUCTION

The efficiency of a Brayton cycle depends among other things upon the turbine inlet temperature and how much of the heat in the turbine outlet gas stream can be recirculated to the gas from the compressor outlet. As the turbine inlet temperature increases so does the operating temperature of the heat exchanger used to recover the exhaust heat. The size of the heat exchanger to transfer this heat must also be kept small in order to keep costs low. Since fluidized beds using ceramic solid particles can operate at very high temperature and have a large amount of heat transfer surface area in a given heat exchanger volume, they make likely candidates for high efficiency low cost Brayton cycle application. This concept was first introduced as air preheaters for MHD cycles.[1,2]

A schematic diagram of the Brayton cycle using fluidized beds is shown in Fig. 1. The turbine exhaust flows into the upper of two fluidized beds with a velocity larger than the minimum fluidization velocity. The particles at the bottom of that bed will become heated. Their temperature will approach the turbine outlet temperature if they remain in contact with the gas long enough. Also, the gas will cool as it transfers its heat to the particles. The hot particles are removed from the bottom of the bed and cold particles are placed on the top of the bed to maintain a constant bed height. The gas leaving the fluidized bed will approach the temperature of the cold particles, if they remain in contact with the gas long enough.

The net effect of the operation of this heat exchanger is to transfer the heat in the outlet gas from the turbine to a stream of solid particles. The solid particles are flowing in a direction opposite to that of the gas.

The heat in this stream of solid particles can, in turn, be transferred back to a gas stream in another fluidized bed. This second bed is the lower bed in Fig. 1. Again, the outlet gas from the compressor flows into a bed at a velocity greater than the minimum fluidization velocity. The gas is to be heated by the solid particles to as high a temperature as possible, so the hottest particles are put on top of the bed. They flow down the bed, giving their heat to the gas until they reach the bottom of the bed where their temperature approaches the temperature of the compressor outlet temperature again if they remain in contact with the gas long enough. They are then removed from the lower bed and sent to the upper bed to be reheated.

The combination of the two fluidized beds and the circulating solid particles constitutes the recuperator for the Brayton cycle. The solids from the upper bed could flow by gravity into the lower bed. However, the lower bed is at a higher pressure (nominally the compressor outlet pressure). But the height of the hot particle transfer tube can be designed so as to provide a static "head" of solid particles equal to the pressure in the vessel. Then the solids will flow into the lower bed. The solid particles can be returned to the upper bed by pneumatic transport, i.e. "dragging" the particles back by a high velocity stream of air.

The efficiency of this Brayton cycle depends upon the amount of air required to transport the solids from the lower to the upper beds as well as the amount of air which "leaks" through the tube which is transporting the solids from the upper bed to the lower bed.

The size of the two beds for a specified power level of the cycle depends upon the velocity of the gas through the beds and the height of the bed. Since the pressure drop of the air flowing through the beds is proportional to the height of the bed there is a trade off between bed size and cycle efficiency.

This paper calculates the effect of particle diameter and bed pressure drop (proportional to bed height) on the size of the recuperator and the efficiency of the cycle. Optimum values of compressor outlet pressure and pressure drop across the beds are found.

CYCLE EFFICIENCY

Fluidized Bed Regenerators

The Brayton cycle which will be analyzed is shown in Fig. 2. While cycle performance can be improved by using turbine reheat and compressor intercooling, it is not important for the comparisons between different types of heat exchangers. The only difference between this cycle and the usual cycle is that the mass flow through the compressor (state points 1 to 2) is greater than through the turbine. The difference in mass flow either "blows" the particles from the lower to the higher, or "leaks" from the high pressure to the low pressure.

The efficiency can be written as Ref. 3:

$$\eta = \frac{E - \left(1 + \frac{\dot{m}_c + \dot{m}_h}{\dot{m}_{turb}}\right)\left(\frac{T_1}{T_4}\right) C}{1 - (1 - E)\eta_{rec} - (1 + C)(1 - \eta_{rec})\left(\frac{T_1}{T_4}\right)} \qquad (1)$$

where

$$E \equiv \eta_{turb}\left[1 - \left(\frac{p_1 + \Delta p_u}{p_2 - \Delta p_\ell - \Delta p_3}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad (2)$$

$$C \equiv \frac{1}{\eta_{comp}}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (3)$$

$$\eta_{rec} \equiv \frac{T_5 - T_6}{T_5 - T_2} \quad (4)$$

(Symbols are defined in Appendix A).

The recuperator effectiveness can be calculated from the heat transfer processes in the regenerators. Equations for gas to gas recuperators have been formulated and solved by Hausen[4] (pp. 202-213). His results can be used by considering (in either regenerator) the gas to be one fluid and the solids to be a counterflow fluid.

Then Hausen's equation for the lower bed becomes

$$\frac{T_{3s} - T_{2s}}{T_{3s} - T_2} = \frac{e^{(1-\tau_\ell)\xi_\ell} - 1}{e^{(1-\tau_\ell)\xi_\ell} - \tau_\ell} \equiv g_\ell \quad (5)$$

$$\frac{T_3 - T_2}{T_{3s} - T_2} = \tau_\ell g_\ell \quad (6)$$

where

$$\frac{\dot{C}_I}{\dot{C}_{II}} = \tau_\ell \equiv \frac{G_{\ell s}C_s}{\rho_{\ell g}u_{o\ell}C_p}; \quad \xi_\ell = \frac{h_{p\ell}6(1 - \epsilon_\ell)H_\ell}{D_p G_{\ell s} C_s} = \frac{US}{\dot{C}_I} \quad (7)$$

since the area of the spheres in a unit volume of bed is $6(1 - \epsilon_\ell)/D_p$ (Ref. 4, p. 333). The equations for the upper bed are:

$$\frac{T_{5s} - T_{6s}}{T_5 - T_{6s}} = \frac{e^{(1-\tau_u)\xi_u} - 1}{e^{(1-\tau_u)\xi_u} - \tau_u} \equiv g_u \quad (8)$$

$$\frac{T_5 - T_6}{T_5 - T_{6s}} = \tau_u g_u \quad (9)$$

$$\frac{\dot{C}_I}{\dot{C}_{II}} = \tau_u = \frac{G_{us}C_s}{\rho_{ug}u_{ou}C_p}; \quad \xi_u = \frac{h_{pu}6(1 - \epsilon_u)H_u}{D_p G_{us} C_s} = \frac{US}{\dot{C}_I} \quad (10)$$

The solid mass flow must be equal in the two beds and two transfer tubes:

$$G_{hs}D_h^2 = G_{\ell s}D_\ell^2 = G_{us}D_u^2 = G_{cs}D_c^2 \quad (11)$$

The gas mass flow is equal the same in both beds so that: $\tau_u = \tau_\ell = \tau$.

The heat transfer coefficients are related to bed conditions by (Ref.5, p.215): $h_pD_p = (1/10)(\rho_g u_o C_p/P_r)$ Also, if there is no heat lost in the transfer tubes $T_{2s} = T_{6s}$ and $T_{3s} = T_{5s}$. Equations (5) and (8) can be solved for T_{2s} and T_{3s}:

$$T_{2s} = \frac{g_\ell T_2 + g_u(1 - g_\ell)T_5}{1 - (1 - g_u)(1 - g_\ell)} \quad (12)$$

$$T_{3s} = \frac{g_u T_5 + g_\ell(1 - g_u)T_2}{1 - (1 - g_u)(1 - g_\ell)} \quad (13)$$

Equation (9) with $T_{6s} = T_{2s}$ can be solved for:

$$\frac{T_5 - T_6}{T_5 - T_2} = \frac{g_\ell g_u \tau_u}{1 - (1 - g_\ell)(1 - g_u)} \quad (14)$$

and Eq. (6) becomes

$$\frac{T_3 - T_2}{T_5 - T_2} = \frac{g_\ell g_u \tau_\ell}{1 - (1 - g_\ell)(1 - g_u)} \quad (15)$$

The recuperator effectiveness can be determined from Eqs. (14) and (4):

$$\eta_{rec} = \frac{g_\ell g_u \tau}{1 - (1 - g_\ell)(1 - g_u)} \quad (16)$$

The maximum value of η_{rec} occurs when $\tau = 1$. This can be seen on physical grounds by noting that this matches the temperatures in the solids to that of the gas. This is equivalent to a counterflow gas to gas recuperator with negligible temperature drop across the separating wall. In this case:

$$g_\ell = \frac{\xi_\ell}{1 + \xi_\ell}; \quad g_u = \frac{\xi_u}{1 + \xi_u} \quad (17)$$

and

$$\eta_{rec} = \frac{1}{1 + 1/\xi_u + 1/\xi_\ell} \quad (18)$$

The recuperator effectiveness can approach 1 if ξ_ℓ and ξ_u (i.e. H_ℓ and H_u) are large enough.

The bed heights and the length of the hot particle transfer line are related to the pressure drops by the momentum equation (Ref. 5, p. 72):

$$\Delta p_\ell = (\rho_s - \rho_{g\ell})(1 - \epsilon_\ell)gH_\ell \quad (19)$$

$$\Delta p_u = (\rho_s - \rho_{gu})(1 - \epsilon_u)gH_u \quad (20)$$

$$p_2 - \Delta p_\ell - p_1 - \Delta p_u = (\rho_s - \rho_{gh})(1 - \epsilon_h)gL \quad (21)$$

We must evaluate the mass flow required to "blow" the cold particles from the lower bed to the upper bed. The momemtum equation (Ref. 5, pp. 389-391) is:

$$p_2 - p_1 = \left(\frac{G_{cs}}{U_s} + \frac{G_{cg}}{U_g}\right) g \, (L + H_u + H_\ell) + \rho_{cg}U_oU_s\left(\frac{G_{cs}}{G}\right) + \left[1 + \frac{\pi}{8}\frac{f_p}{f_g}\left(\frac{\rho_{cg}}{\rho_s}\right)^{\frac{1}{2}} \frac{G_{cs}}{G}\right] \frac{2\rho_{cg}U_o^2}{D_c^2} f_g(L + H_u + H_\ell) \quad (22)$$

where:

$$\rho_{cg} = \frac{p_1 + p_2}{2\bar{R}T_2}$$

$$U_{te} = 8.72 \sqrt{\frac{D_p(\rho_s - \rho_{cg})g}{24.5\ \rho_{cg}}}$$

$$\frac{G_{cs}}{\rho_s} = (1 - \epsilon_c)(U_g - U_{te})$$

$$G_{cg} = \epsilon_c \rho_{cg} U_g$$

$$U_o = \epsilon_c u_g$$

$$Re_c = \frac{\rho_{cg} u_o D_c}{\mu}$$

$$f_p = \left\{5(Re_c \times 10^{-5})^2 - 7.5(Re_c \times 10^{-5}) + 3.2\right\} \times 10^{-4}$$

$$f_g = .0791\ Re_c^{-\frac{1}{4}} \tag{23}$$

It expresses the pressure required for the mass flow G_{cs}. A sensitive parameter in this equation is the void fraction, ϵ_c, in the tube. We choose the curve in Kunii and Levenspiel (Ref. 5, Fig. 17, p. 386).

The "leakage" of mass through the downflow line is (Ref. 5, p. 67):

$$\dot{m}_h = \frac{[p_2 - \Delta p_\ell + p_1 + \Delta p_u]D_p^2\epsilon_h^3[p_2 - \Delta p_\ell - p_1 - \Delta p_u]\pi D_h^2}{600\ \bar{R}\ (T_3 + T_5)(1 - \epsilon_h)^2 L}$$

It is negligibly small for all cases of interest and will be neglected.

All of the terms in the efficiency equation can be calculated. The fluidized bed volume required can also be determined:

$$V = \frac{\pi}{4}\left\{D_\ell^2 H_\ell(1 + F_{BL}) + D_u^2 H_u(1 + F_{BU})\right\} \tag{24}$$

where F_{BL} and F_{BU} are the terms representing the free board volume. This is the open volume above the bed to minimize particle carryover. We will arbitrarily make the free board volume equal to the bed volume.

The power output, P, is:

$$P = \dot{m}_{turb} C_p T_4 \left\{E - \left(1 + \frac{\dot{m}_c + \dot{m}_h}{\dot{m}_{turb}}\right)\left(\frac{T_1}{T_4}\right) C\right\} \tag{25}$$

The specific volume will be defined as the fluidized bed volume, V, divided by the power.

Shell and Tube Heat Exchanger

The performance of the fluidized bed regenerator can be compared to a shell and tube heat exchanger. Equation (1) holds for the efficiency by setting $\dot{m}_c$ and $\dot{m}_h$ equal to zero. The recuperator effectiveness is given in Jakob (Ref. 4, Eqs. 34-37 and 34-21, p. 208) with $\dot{m}\ c_p = \dot{C}_I = \dot{C}_{II}$ as

$$\eta_{rec} = \frac{1}{1 + \frac{\dot{m}C_p}{US}} \tag{26}$$

We will assume that

$$(\rho u)_{sh} = (\rho u)_t = \rho u \tag{27}$$

and that the flow area on the shell side is equal to the flow area inside the tubes.

If $h_i = h_o = h = \frac{U}{2}$ and the tube length is L_t, then

$$\eta_{rec} = \frac{1}{1 + \frac{\rho u c_p D_t}{2hL_t}} = \frac{1}{1 + \frac{Re_t \mu c_p}{2hL_t}} \tag{28}$$

The heat transfer coefficient (Ref. 6, p. 547) is:

$$hD_t = \frac{\mu c_p}{Pr}(.027)R_{et}^{.8}$$

The length of the tubes can be related to the pressure drop (Ref. 6, Eqs. 21-37, p. 733):

$$\frac{\Delta p}{p_1 + \frac{\Delta p}{2}} = \frac{.3164}{R_e^{\frac{1}{4}}}\frac{\gamma}{2} M_t^2 \frac{L_t}{D_t} \tag{29}$$

and

$$M_t^2 = \frac{2U_t^2}{\gamma\bar{R}\quad T_4(1 - E)(2 - \eta_{rec}) + \eta_{rec}T_1(1 + C)} \tag{30}$$

The mass flow rate is:

$$\dot{m} = \rho u \pi D_{sh}^2 \Big/ 8\ Re_t \tag{31}$$

where D_{sh} is the overall outside diameter of the recuperator.

The power output is obtained from Eq. (25) again with $\dot{m}_h$ and $\dot{m}_c = 0$. The specific volume for the shell and tube recuperator is:

$$\frac{V}{P} = \frac{\frac{\pi}{4} D_{sh}^2 L_t}{P} = \frac{2D_t L_t}{C_p \mu Re_t T_4(E - T_1/T_4 C)} \tag{32}$$

SPECIFICATION OF PARAMETERS

We will examine the effects of varying certain parameters with respect to fluidized bed performance on the efficiency of the cycle and the size of the recuperators. To do this we will specify certain of the parameters with values typical of Brayton cycle systems burning a fuel and using the combustion products as working fluid.

We will choose air as a typical working fluid and boron nitride as a typical high temperature ceramic. The void fraction for the transport of the cold particles can be found for boron nitride (density is 2100 kg/m^3) in Ref. 5, p. 386. Typical turbine and compressor efficiencies and pressure drop across the the heat source will be chosen. They are specified as follows:

$$\eta_{comp} = .88$$

$$\eta_{turb} = .90$$

$$\frac{\Delta p_3}{p_2} = .04$$

The inlet conditions are $T_1 = 330$ K, $p_1 = 10$ N/cm^2. The gas is assumed to be air and the properties are evaluated at 900° K:

$$\mu = 4.1\text{x}10^{-5} \text{ kg/m sec}$$

$$\bar{R} = 280 \text{ j/kg } ^oK$$

$$c_p = 1 \text{ kj/kg } ^oK$$

$$Pr = .7$$

$$\gamma = 1.4$$

Fluidized Bed Regenerators

The solid will be taken as boron nitride with:

$$\rho_s = 2100 \text{ kg/m}^3$$

$$c_s = 1.6 \text{ kj/kg } ^oK$$

$$\epsilon_c = .973$$

The void fraction in the down tube is chosen as .4 and in both fluidized beds as .45. This corresponds to dense and normal packing of particles with sphericity of .8 (Ref. 4, p. 66). The fractional pressure drops will be made equal $[(\Delta p_\ell/p_2) = (\Delta p_u/p_1)]$ and the height of the low pressure will be set equal to the diameter, $H_u = D_u$ for the calculation of output power. If the bed height is less than the diameter it may be unstable and a "channeling" might occur through which most of the flow may pass. If the height gets much greater than the diameter then the bed may get unstable and "slugging" might occur (Ref. 5, p. 75).

A parameter associated with bed performance is the superficial velocity (actual velocity divided by the void fraction). This must be higher than the minimum fluidization velocity, but not so high that significant bubbling occurs. Higher velocity allows more heat to be transferred and reduces equipment size. However, as gas velocity increases there will be mixing in the vertical direction because of an increased number of bubbles forming and rising due to their bouyancy. This mixing can reduce the effectiveness of the heat exhchanger by bringing the inlet and outlet gas temperatures closer together. Bubbles appear in gas-solid fluidized beds because of the large density ratio (Ref. 5, Eqs. (22) and (32) in Chapter 3). However, if the superficial velocity is two times the minimum fluidization velocity (ref. 5, p. 134) then less than 10% of the bed volume will contain bubbles and mixing should be minimized. We assume that velocity ratio in our calculations.

In order to calculate the volume of the beds we specify that the diameter of the pipe carrying the solids to the upper bed is 10 cm. This is important only in calculating the frictional pressure drop for the gas-tube interaction and is unimportant compared to the gas-particle interactions. Therefore, we calculate the specific volume of the beds by dividing the power output by the total recuperator volume. We have 4 parameters left to vary; particle diameter, fractional pressure drop, the compressor outlet pressure, and the turbine inlet temperature.

Specifying these parameters in the upward solids transport line equation (Eq. (22)) determines the mass flow rates of both the gas and the solids. This, in turn, can be used to calculate bed heights and recuperator effectiveness and finally, to calculate efficiency.

The system power level can be calculated by specifying a fluidized bed diameter, rather than the cold particle transfer tube diameter. This will be done by setting the diameter of the upper (lower pressure) diameter equal to its height.

Shell and Tube Recuperator

The same component efficiencies and fluid properties will be chosen as before. However, the tube diameter will replace the particle diameter. Also, the Mach number will be varied in addition to the pressure drop and compressor outlet pressure.

RESULTS

First, a turbine inlet temperature of 1250° K is selected. Then $\Delta p/p$ and D_p are selected and compressor outlet pressure varied. As the pressure increases the specific volume decreases and efficiency increases. At a certain pressure the efficiency reaches a maximum and then decreases along with the specific volume as the pressure continues to increase. This is characteristic of all recuperated Brayton cycles. We will set the pressure at the value corresponding to the optimum efficiency. In this fashion the diameter of the particle and the fractional pressure drop are sufficient to specify the specific volume and the efficiency. The results are shown in Fig. 3(a) for turbine inlet temperature of 1250° K and Fig. 3(b) for turbine inlet temperature 1150° K.

The cycle efficiency is sensitive to turbine inlet temperature. A comparison of Figs. 3(a) and (b) shows that the efficiency increases about four percentage points when the turbine inlet temperature is increased 100 K from 1150 to 1250.

At a given fractional pressure drop the efficiency decreases with increasing particle diameter because the surface area available for heat transfer decreases. This, in turn, lowers the recuperator effectiveness and, ultimately, the cycle efficiency.

Generally, the efficiency improves with decreasing particle size. Also for a given particle size efficiency improves with increasing fractional pressure drop up to a point. In this range, the recuperator effectiveness was increasing rapidly enough to offset the increased compressor power required to make up for that drop. After that point, the recuperator effectiveness increase is not sufficient to overcome the increased losses.

The fractional pressure drop at this turning point is a function of the particle diameter and is plotted in Fig. 4 for both 1150 K and 1250 K. The optimum value increases with particle diameter. The efficiency value increases with increasing particle diameter, while the specific volume decreases slightly. At the larger particle diameters, however, the power output is higher. The fluid velocity, and hence mass flow, increases as the size of the particle increases because of the larger entrainment velocity.

For the shell and tube recuperator with a specified fractional pressure drop, tube diameter and flow Mach number there is a compressor outlet pressure which also maximizes the efficiency. Again we choose that pressure as our operating point. The results can be seen in Fig. 5 for a fixed fractional pressure drop of .04. The recuperator specific volume increases with increasing tube diameter for any Mach number and increases with decreasing Mach number for any tube diameter. The performance is similar for other pressure drops, with the specific volume increasing with increasing pressure drop for any tube diameter and Mach number.

On the other hand, efficiency doesn't change with increasing tube diameter at a fixed Mach number and pressure drop, it increases with decreasing Mach number for a fixed tube diameter and pressure drop, and it has a maximum for a fixed Mach number and tube diameter as the pressure drop increases. When the pressure drop is too low the heat transfer is too low and not enough heat in the turbine exhaust is recovered. When the pressure drop is too high the compressor work is too large and the increased heat recovery cannot compensate.

Generally, comparing Figs. 3 and 5 one can see that for comparable efficiency the fluidized bed regenerators are more compact. This is the result of the more favorable surface to volume ratio of the particles ($6/D_p$) compared to the tubes ($2/D_t$).

CONCLUSIONS

The high operating temperature capability of fluidized bed regenerators makes them an attractive concept for advanced cycle application.

Calculations comparing these fluidized bed regenerators to shell and tube heat exchangers at the same conditions with solid density 2.1 grams/cm^3 and gas velocity of twice the minimum fluidization velocity have been made. These calculations show that the total volume of the shell and tube heat exchangers is two to three times the total volume of the fluidized beds. However, the total amount of power which can be handled by each of these fluidized beds is limited to probably less than a megawatt unless very shallow beds are considered. The power may be increased by considering rotating beds where the acceleration on the solids can be increased above 1 gram (9.8 m/sec^2)[7,8].

APPENDIX - SYMBOLS

c, C_p	specific heat
C	compressor parameter defined in Eq. (3)
$\dot{C}_I, \dot{C}_{II}$	parameters defined in Ref. 4
D	diameter
E	turbine parameter defined in Eq. 2
f	friction factors given in Eq. (22)
F_{BU}, F_{BL}	ratio of free board volume to bed volume
g	gravity acceleration, 9.806 m^2/sec
G	mass flow per unit area
h	heat transfer coefficient
H	bed heights
L	length of hot particle transfer line
$\dot{m}$	mass flow rate
M	Mach number
Pr	Prandtl number
p	pressure
Δp	pressure drops
q	parameters defined in Eq. (5) and (8)
$\bar{R}$	gas constant
Re	Reynolds number
S	surface area defined in Ref. 4
T	temperature
U	heat transfer coefficient in Ref. 4
V	heat exchanger volume
γ	ratio of specific heats
ϵ	void fraction
η	efficiency
μ	gas viscosity
ξ	parameters defined in Eq. (7) and (10)
ρ	density
τ	parameters defined in Eq. (7) and (10)

Subscripts

c	cold particle transfer line
comp	compressor
g	gas
h	hot particle transfer line
hs	heat source
ℓ	lower bed
o	superficial velocity
rec	recuperator
s	solid
sh	shell
t	tube
te	terminal
turb	turbine
u	upper bed

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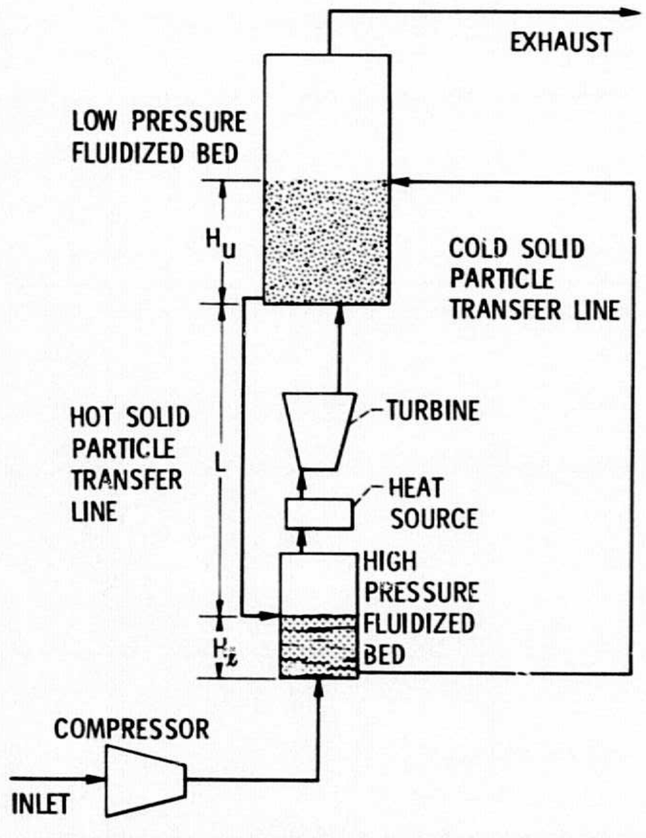


Figure 1. - Schematic diagram of open cycle gas turbine system with fluidized bed heat regenerators.

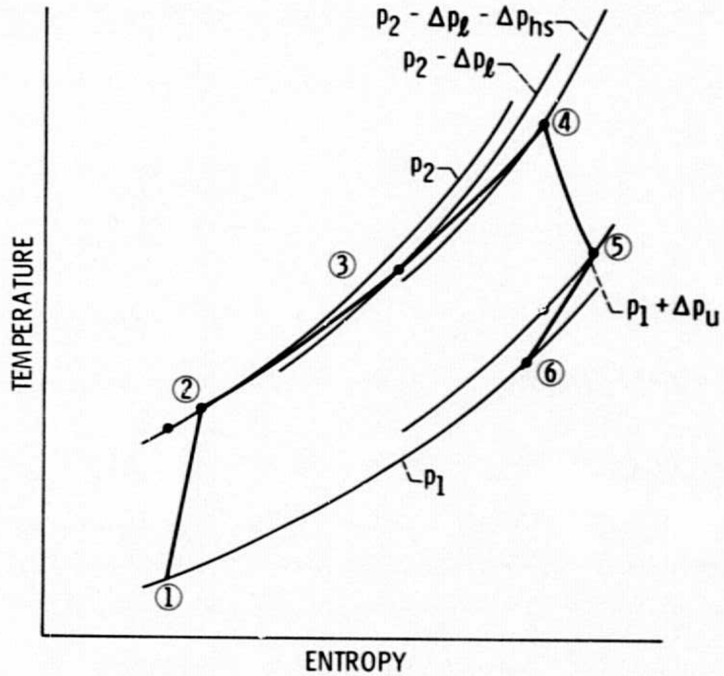
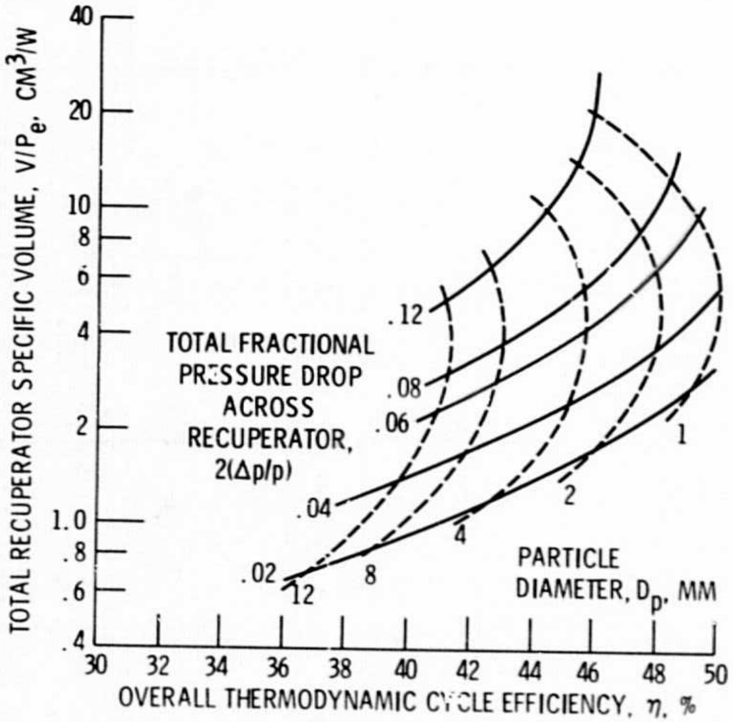
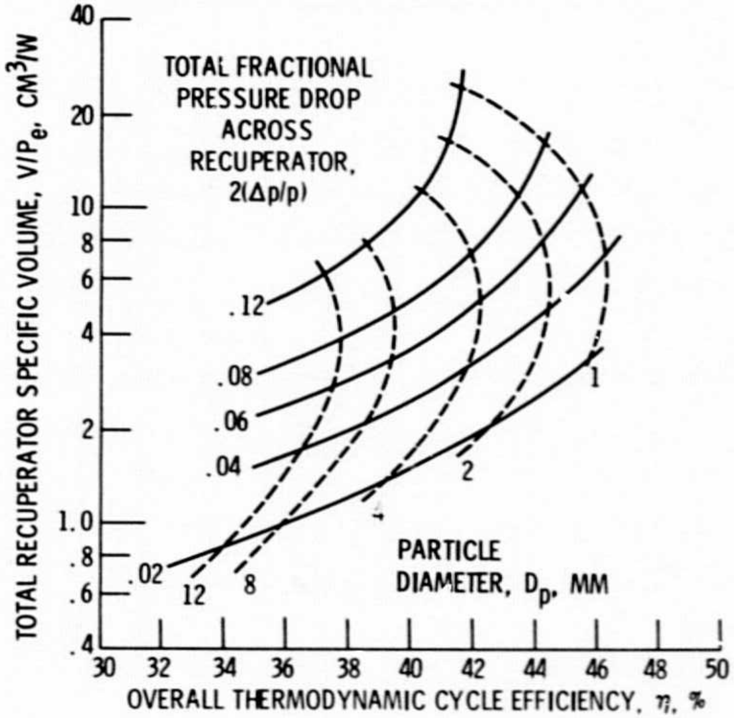


Figure 2 - Brayton cycle state points on the temperature-entropy diagram.



(a) TURBINE INLET TEMPERATURE, K, 1250.

Figure 3. - Effect of particle diameter and total recuperator fractional drop on the total recuperator specific volume and the overall thermodynamic cycle efficiency for fluidized bed regenerators.



(b) TURBINE INLET TEMPERATURE, K, 1150.

Figure 3. - Concluded.

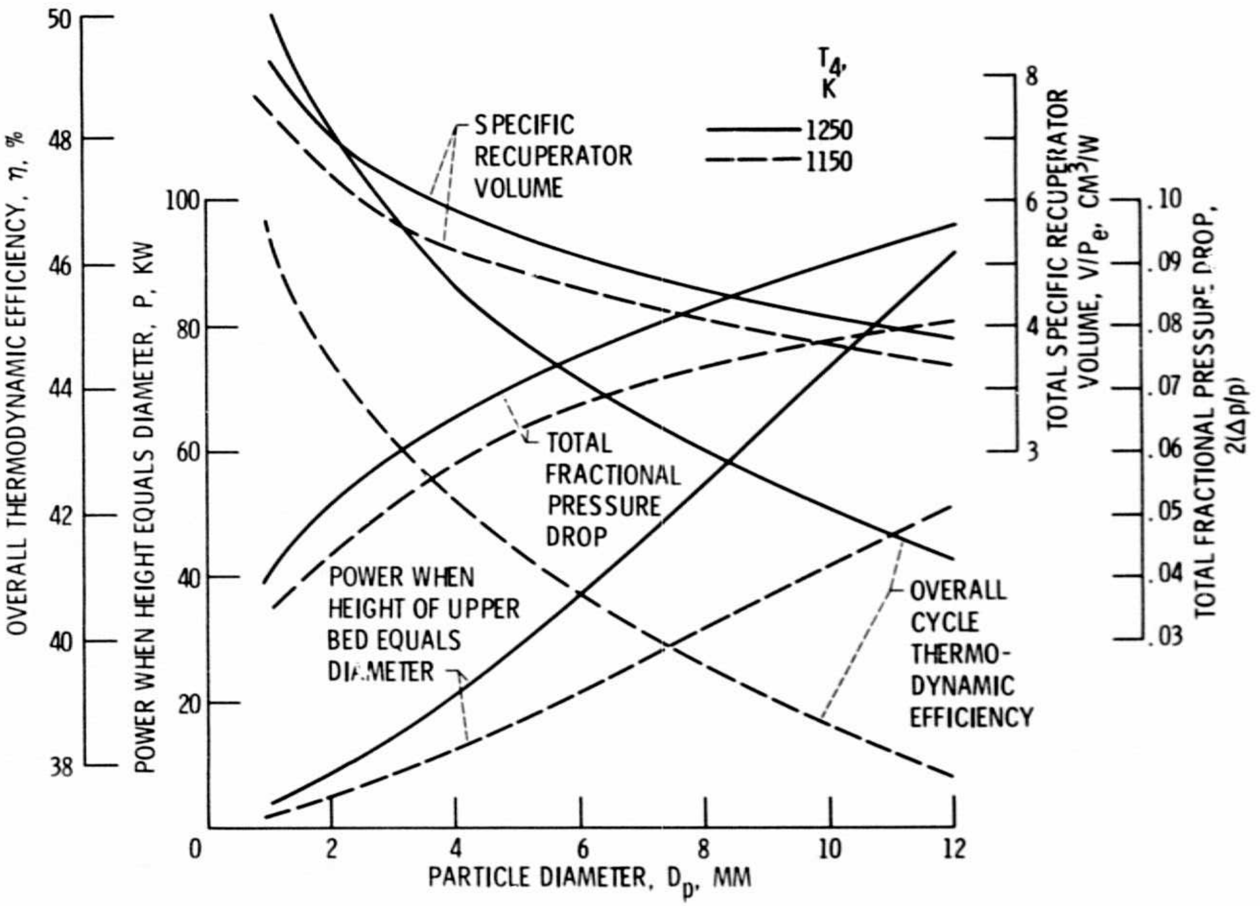


Figure 4. - Fluidized bed recuperator parameters at "optimum" compressor outlet pressure and "optimum" fractional pressure drop across the beds.

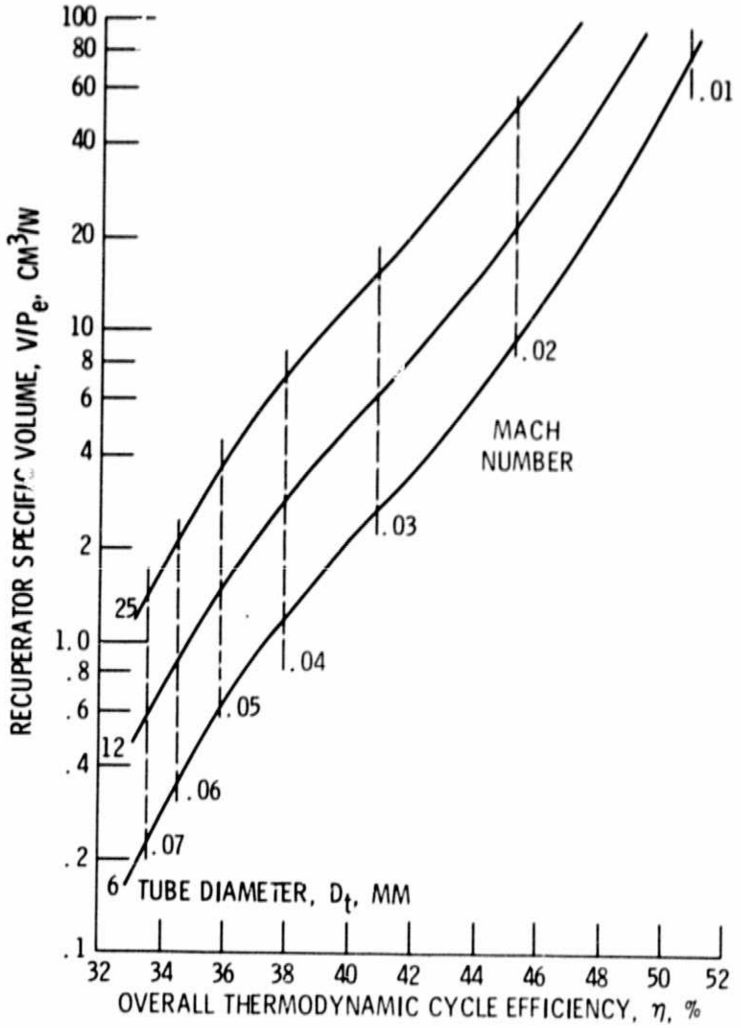


Figure 5. - The effect of tube diameter and gas flow Mach number on the recuperator specific volume and the overall thermodynamic cycle efficiency for shell and tube recuperator.