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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 the incidence of heat transfer. For this reason 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 temperatures 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 MSID cycles.

A schematic diagram of the Brayton cycle using fluidized beds is shown in Fig. 1. The turbine exhaust enters into the upper of two fluidized beds with a velocity greater 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 gas stream 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 isleaves" 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:

\[ \eta = \frac{1 + \frac{\dot{m}_p + \dot{m}_g}{\dot{m}_g} \left( \frac{T_1}{T_2} \right)}{1 - (1 - E) \eta_{rec} - (1 + C)(1 - \eta_{rec}) \left( \frac{T_1}{T_2} \right)} \]  

(1)

where

\[ E = \left( \frac{p_1 + \Delta p_0}{p_2 + \Delta p_2 - \Delta p_3} \right)^{\gamma - 1} \]  

(2)
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 (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

\[ \frac{T_3 - T_2}{T_3 - T_2} = \frac{1 - (1 - T_2)g_2}{1 - (1 - T_2)g_2} \]

(5)

where

\[ \frac{C}{C^*} = 1 - \frac{1}{g_2} \left( \frac{P_2}{P_1} \right) \]

and

\[ n_{rec} = \frac{T_3 - T_2}{T_3 - T_2} \]

(4)

(Symbols are defined in Appendix A).

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

\[ n_{rec} = 1 - \frac{1}{1 - g_2 (1 - g_2)} \]

(16)

The maximum value of \( n_{rec} \) occurs when \( T_2 = 1 \). 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:

\[ n_{rec} = \frac{1}{1 + 1/c_g + 1/c_{gs}} \]

(18)

The recuperator effectiveness can approach 1 if \( c_g \) and \( c_{gs} \) (i.e. \( H_1 \) and \( H_2 \)) 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):

\[ \Delta P_k = \left( \rho_s - \rho_g \right)\left( 1 - c_g \right) \frac{\Delta T}{g_k} \]

(19)

\[ \Delta P_{u} = \left( \rho_s - \rho_g \right)\left( 1 - c_g \right) \frac{\Delta T}{g_u} \]

(20)

\[ P_2 - P_1 = \left( \frac{G_{cs}}{G_{c}} + \frac{G_{cr}}{G_{r}} \right) \frac{g}{L + H_{u} + H_{l}} \]

(21)

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

\[ P_2 - P_1 = \left( \frac{G_{cs}}{G_{c}} + \frac{G_{cr}}{G_{r}} \right) \frac{g}{L + H_{u} + H_{l}} \]

(22)
where:

\[ \frac{1}{P_1 + P_2} = \frac{1}{\sqrt{\frac{\Delta p}{g c} (c_g - c_s) \varepsilon}} \]

\[ U_{te} = 8.72 \sqrt{\frac{\Delta p}{g c} (c_g - c_s) \varepsilon} \]

\[ G_{ct} = (1 - c_s) (U - U_{te}) \]

\[ G_{cg} = c_g c_t g R \]

\[ U_0 = c_u c_g R \]

\[ R_e = \frac{v c_g u D}{u} \]

\[ f_p = \left( \frac{5 (R e_c \times 10^{-5})}{1 + 2 \times 10^{-5}} \right) \]

\[ f_p = 0.0791 R e_c \] (23)

It expresses the pressure required for the mass flow rate, \( G_{ct} \). A sensitive parameter in this equation is the void fraction, \( c_s \), 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):

\[ \frac{\Delta p}{P_2 - \Delta p_f} = \frac{1}{600 R (T_3 + T_5) (1 - c_s)} \]

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:

\[ V = \frac{\pi}{2} \left[ D_h (1 + F_{BL}) + D_t (1 + F_{BT}) \right] \] (24)

where \( F_{BL} \) and \( F_{BT} \) 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:

\[ P = \frac{\dot{m}_{turb} C_p T_i}{E - \left( \frac{\dot{h}_s + \dot{h}_t}{\dot{h}_{turb}} \right)} \] (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 considered to a shell and tube heat exchanger. Equation (1) holds for the efficiency by setting \( \dot{h}_t \) and \( \dot{h}_s \) equal to zero. The recuperator effectiveness is given in Jakob (Ref. 4, Eqs. 34-37 and 34-21, p. 298) with \( \dot{h}_t = \dot{h}_1 - \dot{h}_0 \) as

\[ n_{rec} = \frac{1}{1 + n_{rec} (1 + C)} \] (26)

We will assume that

\[ (\rho u)_{sh} = (\rho u)_t = \rho u \] (27)

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

If \( h = h_0 \) and the tube length is \( L_t \), then

\[ n_{rec} = \frac{1}{1 + \frac{h c_{turb} D_t}{2 L_t}} \] (28)

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

\[ h = \frac{h c_{turb} D_t}{2 L_t} \] (29)

The length of the tubes can be related to the pressure drop (Ref. 6, Eqs. 21-37, p. 33):

\[ L_t = \frac{2 h c_{turb} D_t}{2 h} \] (30)

The mass flow rate is:

\[ \dot{m} = \frac{D_t^2}{8 R e_t} \] (31)

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

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

\[ \frac{V}{P} = \frac{\dot{m} c_{turb} D_t}{P} = \frac{2 D_t L_t}{C_p u R e_t (E - T_1/T_5)} \] (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
com., soror efficiencies and pressure drop across the
the heat source will be chosen. They are specified as
follows:
\[ \eta_{\text{comp}} = 0.88 \]
\[ \eta_{\text{turbo}} = 0.90 \]
\[ \Delta P_3 / P_2 = 0.04 \]
The inlet conditions are \( T_1 = 330 \text{ K}, \ p_1 = 10 \text{ N/cm}^2 \). The gas is assumed to be air and the properties are evaluated at 900° K:
\[ \mu = 4.1 \times 10^{-5} \text{ kg/sec} \]
\[ \rho = 1.26 \text{ kg/m}^3 \]
\[ c_p = 1 \text{ kJ/kg K} \]
\[ f = 0.7 \]
\[ \gamma = 1.4 \]
Fluidized Bed Regenerators
The solid will be taken as boron nitride with:
\[ \rho_s = 2100 \text{ kg/m}^3 \]
\[ c_p = 1.6 \text{ kJ/kg K} \]
\[ c_c = 0.973 \]
The void fraction in the down tube is chosen as \( \alpha = 0.8 \) and in both fluidized beds as \( \alpha = 0.45 \). This corresponds to dense and normal packing with sphericity of \( \phi = 0.8 \) (Ref. 4, p. 66). The fractional pressure drops will be made equal ([\( \Delta P_3 / P_3 \) = \( \Delta P_2 / P_2 \)]) and the height of the low pressure will be set equal to the diameter, \( H_3 = D_3 \), 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 buoyancy. This mixing can reduce the effectiveness of the heat exchanger 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 cal-

\[ V = \frac{Q}{\pi D^2 / 4} \]

\[ P_f = \frac{F \mu D^2}{8 \pi L} \]

\[ \Delta P = \frac{P_1 - P_2}{L} \]

\[ \Delta H = \frac{Q}{D^2 \rho g} \]

\[ P_R = \frac{P_1 - P_2}{L} \]

\[ \Delta P_{\text{tot}} = \Delta P_f + \Delta P_{\text{fric}} + \Delta P_{\text{el}} \]

\[ \eta_{\text{comp}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turbo}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{recup}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \Delta P_{\text{recup}} = \frac{P_{\text{in}} - P_{\text{out}}}{L} \]

\[ \eta_{\text{cycle}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turb}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{comp}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turbo}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{recup}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \Delta P_{\text{recup}} = \frac{P_{\text{in}} - P_{\text{out}}}{L} \]

\[ \eta_{\text{cycle}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turb}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{comp}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turbo}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{recup}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \Delta P_{\text{recup}} = \frac{P_{\text{in}} - P_{\text{out}}}{L} \]

\[ \eta_{\text{cycle}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]

\[ \eta_{\text{turb}} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}} \]
because of the larger entrainment velocity.

For the shell and tube recuperator with a specified frictional 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/Dp) compared to the tubes (2/Dt).

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/cm³ 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/sec²).8.

REFERENCES

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.

(a) TURBINE INLET TEMPERATURE, K, 1250.

(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.