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Abstract

The expression $\frac{M(Pr)^{2/3}}{(M\,C_p)^3}$ which is often used to compare the merits of various gas coolants is derived and the errors involved in using this term are discussed. An example using CO_2 and He is shown to illustrate the difference between the true pumping power required and that predicted by the above expression.

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COMPARISON OF GASES FOR USE AS THE COOLANT IN A GAS-COOLED REACTOR

There is no simple and accurate method of comparing the merits of different gases as a coolant in a gas-cooled reactor. One very common method is shown below. The basic equations for the comparison are as follows:

$$h = \frac{0.023}{Re^{.2}} \frac{V \rho C_p}{(Pr)^{2/3}} \tag{1}$$

$$Q = h A_s \Delta t_w \tag{2}$$

$$Q = w C_p \Delta t_g = V \rho A_c C_p \Delta t_g \tag{3}$$

$$\Delta H_f = 4 f \frac{V^2}{2g} \frac{L}{D_e} \tag{4}$$

$$W = w \Delta H_f = V \rho A_c \Delta H_f \tag{5}$$

The object then is to determine which gas requires the smallest amount of work to deliver a given amount of heat from the reactor core.

Combining equations (1) and (2)

$$Q = \frac{0.023}{Re^{.2}} \frac{V \rho C_p}{(Pr)^{2/3}} A_s \Delta t_w \tag{6}$$

Combining equations (4) and (5)

$$W = V \rho A_c 4 f \frac{V^2}{2g} \frac{L}{D_e} \tag{7}$$

Dividing (7) by (6)

$$\frac{W}{Q} = \frac{V \rho A_c 4 f \quad V^2 \quad L \quad (Pr)^{2/3}}{\left(\frac{.023}{Re^{.2}}\right) V \rho C_p \quad 2g \quad D_e \quad A_s \Delta t_w} \tag{8}$$

Substituting (3) in (8)

$$\frac{W}{Q} = \frac{4 f \quad Q^2 \quad L \quad (Pr)^{2/3}}{\left(\frac{.023}{Re^{.2}}\right) 2g \quad D_e \quad A_s \Delta t_w \Delta T_g^2 A_c \rho^2 C_p^3} \tag{9}$$

Also $\rho = \frac{PM}{RT}$ and $f = \frac{.046}{Re^{.2}}$ therefore

$$\frac{W}{Q} = \frac{4 \quad Q^2 L \quad R^2 \quad T^2 \quad (Pr)^{2/3}}{g A_s A_c \Delta t_w \Delta t_g^2 \quad D_e \quad P^2 \quad M^2 \quad C_p^3} \tag{10}$$

or

$$\frac{W}{Q} = \frac{4\,Q^2\;L\;R^2\;T^2}{g\,A_s\,A_c\,\Delta t_w\,\Delta t_g^2\;D_e\;P^2}\;\frac{M\,(Pr)^{2/3}}{(M\,C_p)^3} \tag{11}$$

Although the last term in equation (11) is the only term involving the properties of the gas, it does not follow that the gas which has the smallest value of

$$\frac{M\,(Pr)^{2/3}}{(M\,C_p)^3}\;*$$

will have the smallest required pumping power. In a reactor the variation of heat flux along a fuel channel is independent of the gas, and the temperature profile of the gas is a function only of the gas temperature in and out of the channel. In calculating the performance of a reactor the heat transfer coefficient may be determined by using the properties of the gas at the average temperature and then treated as a constant along the length of the channel. This approximation is usually good to within 5% of the true integrated value of the coefficient and is probably within the accuracy of the equations and data used to determine the coefficient. With the gas temperatures as a function only of its location in the reactor and the heat transfer coefficient a constant, the temperature of the fuel element and its cladding is a function only of its location in the reactor. For all gas-cooled reactors proposed or built to date either the temperature of the fuel element or the clad has limited the reactor output. If it is assumed that the maximum allowable fuel element or clad temperature is independent of the gas, and with the temperature of both the fuel element and the gas independent of the gas, then it follows that the heat transfer coefficient must be the same regardless of the gas used as a coolant. The heat transfer coefficient for gases of different properties will not be the same unless the geometry of the system is altered when a different gas is used. The fallacy then of using only the last term of equation (11) is that the terms involving the geometry of the coolant channel cannot be treated as constants.

If the inlet and exit gas temperatures and the maximum fuel element temperature are fixed, then equations (1) and (3) give a relation between the gas properties and the geometry of the system.

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* The expression

$\frac{M\,(Pr)^{2/3}}{(M\,C_p)^3}$ is usually simplified to $\frac{M}{(M\,C_p)^3}$ with the variation of Pr assumed negligible. This expression has appeared repeatedly in the literature [1,2,3] concerned with gas-cooled reactors. In one case[1] the expression is presented as an absolute criteria of the heat transfer merits of a gas while another[3] states "the differences are not so marked as expressions like $M^2C_p^3$ suggest".

$$h = \frac{0.023}{Re^{.2}} \frac{V \rho C_p}{(Pr)^{2/3}} \tag{1}$$

$$Q = V \rho A_c C_p \Delta t_g \tag{3}$$

also $$Re = \frac{D V}{\mu} . \tag{12}$$

Combining (1), (3) and (12)

$$\frac{h \Delta t_g^{.8}}{0.023} = \frac{C_p^{.2} Q^{.8} \mu^2}{D_e^{.2} A_c^{.8} (Pr)^{2/3}} = \text{constant} \tag{13}$$

also $$D_e = \frac{4 A_c}{W_p} . \tag{14}$$

From equations (13) and (14) it becomes obvious that the relative merits of different coolant gases cannot be determined until the configuration of the fuel elements and the channel have been fixed. If the channel is assumed to be circular and the fuel elements made up of one or more circular rods then

$$A_c = \frac{\pi}{4} \left[D_c^2 - N(D_R)^2\right] \tag{15}$$

and $$W_p = \pi \left[D_c + N(D_R)\right]$$

and $$D_e = \frac{4 A_c}{W_p} = \frac{D_c^2 - N(D_R)^2}{D_c + N(D_R)} \tag{16}$$

From equations (13), (15) and (16) it can be seen that several dimensions must be fixed. If the number of rods and their diameter are fixed then the channel diameter can be found for any heat output per channel. If the gas properties are changed then a new channel diameter must be found to satisfy the equations. Once the channel diameter and therefore the free flow area are known it is then a simple matter to find the velocity and the work required to overcome the friction losses. It should be noted that equation (4) and therefore equation (11) are for the core friction loss only. There are also expansion and contraction losses in the core. These will depend only on the gas velocity and may be of the same order as the friction loss. There are also losses in the system external to the core, but these are usually relatively small.

Given below is a comparison of the pumping power required for a system using both CO_2 and He. The reactor choosen for the comparison is a design[4] by Kaiser Engineers and Nuclear Products-ERCO in which CO_2 is the proposed coolant. The following design data were taken from Tables 3.1.1 and 3.1.4 of reference 4.

Type of Fuel	7 slug UO_2 cluster
Fuel Slug Diameter	0.75 in.
I.D. of Graphite Sleeve	3.0 in.
Core Height	25.75 ft
Reactor Thermal Output	600 Mw
Pumping Power	28 Mw (Electrical)
Inlet Gas Temperature	473°F
Mean Exit Gas Temperature	1000°F
Reactor Coolant Flow	14×10^6 lb/hr
Reactor Inlet Pressure	400 psia
Maximum Cladding Temperature	1300°F
Coolant Mass Velocity in Center Channel	7.4×10^5 lb/hr ft

In comparing the performance of the two gases the properties and also the heat transfer coefficient are determined at the average temperature and are treated as being constant. It is also assumed that the mixed mean exit temperature of the gas from the reactor is identical to the temperature leaving the center reactor channel. This can be done by orificing the the channels so that the flow through any channel is proportional to the heat generated in that channel. Also the maximum fuel element temperature in any channel will be less than that of the center channel. This then allows one to calculate the overall performance of a reactor on the basis of the center channel only.

The gas properties were taken at 740°F and are as follows:

	CO_2	He
Specific heat	0.27	1.248 Btu/lb °F
Viscosity	1.95×10^{-5}	2.28×10^{-5} lb/sec ft
Prandtl No.	0.72	0.734
Density	1.373	0.1247 lb/ft^3

The heat transfer coefficient is calculated from equation (1) and for CO_2 with a mass velocity of 7.4×10^5 lb/hr ft^2

$$h = \frac{0.023 \times 7.45 \times 10^5 \times 0.27}{\left(\frac{D_e \times 7.45 \times 10^5}{0.0702}\right)^{0.2} \quad 0.72^{2/3} \quad 3600}$$

For a channel diameter of 3.0 in. and seven 0.75 in. rods

D_e = 0.0512 ft
A_c = 0.0276 ft
h = 0.114 Btu/sec ft^2 °F
V = 149 ft/sec
Re = 5.4×10^5

For a Re of 5.4×10^5 and for commercial tubing the fanning friction factor

$$f = 0.004$$

$$\Delta H_f = 4 f \frac{V^2}{2g} \frac{L}{D_e}$$

$$= 2780 \text{ ft lb/lb.}$$

The expansion and contraction losses in the core are assumed to be as follows:

inlet loss to core $= \frac{1}{2} \frac{V^2}{2g}$ (V at inlet temperature)

fuel element expansion and contraction loss $= 1 \frac{V^2}{2g}$ (V at average temperature)

exit loss from core $= 1 \frac{V^2}{2g}$ (V at exit temperature)

or

$$\Delta H \text{ (expansion and contraction)} = \frac{V^2_{avg}}{2g} \left[.5\left(\frac{473}{736}\right) + 1 + 1\left(\frac{1000}{736}\right)^2 \right]$$

$$= 0.0475\, V^2_{avg}$$

$$= 1050 \text{ ft lb/lb.}$$

In the ORNL gas-cooled reactor study[5] the head loss in the external circuit could be represented by the equation:

$$\Delta H_{external} = 2.78 \times 10^{-12} \left(\frac{W_T}{\rho}\right)^2 .$$

Assuming that the external circuit in the Kaiser Engineers-Nuclear Products study is similar to that of the ORNL study the external head loss is found to be

$$\Delta H_{external} = 2.78 \times 10^{-12} \left(\frac{14 \times 10^6}{1.373}\right)^2 = 290 \text{ ft lb/lb}$$

and the total head loss is

$$\Delta H_T = 2780 + 1050 + 290 = 4120 \text{ ft lb/lb.}$$

When He is substituted for CO_2 it is assumed that the only change to be made to the system is an enlargement of the diameter of the coolant channel. As stated previously the coefficient must be the same as for CO_2.

$$h = 0.114 = \frac{0.23}{Re^{.2}} \frac{\rho V C_p}{(Pr)^{2/3}} \quad \text{Btu/sec ft}^2\ {}^{o}F$$

and

$$0.114 = \frac{0.023 \times 0.1247 \times V \times 1.248}{\left(\frac{D_e V \times 0.1247}{2.28 \times 10^{-5}}\right)^{0.2} (0.734)^{2/3}}$$

Also the temperature rise through the reactor must be the same as for CO_2. For this to be true

$$(V \rho A_c C_p)_{CO_2} = (V \rho A_c C_p)_{He}$$

Both of the above equations are satisfied for a channel diameter of 3.3 in. with

$$D_e = 0.0716 \text{ ft}$$
$$A_c = 0.0386 \text{ ft}$$
$$V = 254 \text{ ft/sec}$$
$$Re = 9.95 \times 10^4$$

The friction factor is then 0.0055 and

$$\Delta H_f = 4 \times 0.0055 \frac{(254)^2}{64.4} \times \frac{25.75}{0.0716} = 7920 \text{ ft lb/lb}$$

$$\Delta H(\text{expansion and contraction}) = 0.0475\ (254)^2$$
$$= 3060 \text{ ft lb/lb}$$

$$\Delta H_{external} = 2.78 \times 10^{-12} \left(\frac{3.03 \times 10^6}{0.1247}\right)^2 = 1640 \text{ ft lb/lb}$$

$$\Delta H_T = 7920 + 3060 + 1640 = 12{,}620 \text{ ft lb/lb}$$

The ratio of the pumping power of CO_2 to that of He is

$$\frac{\text{Power to } CO_2}{\text{Power to He}} = \frac{14 \times 10^6 \times 4120}{3.03 \times 10^6 \times 12{,}620} = 1.51 .$$

It is interesting to note that if the last term in equation (11) were used to evaluate the gases the ratio would be

$$\frac{\text{Power to } CO_2}{\text{Power to He}} = \frac{\left[\dfrac{M(Pr)^{2/3}}{(M\,C_p)^3}\right]_{CO_2}}{\left[\dfrac{M(Pr)^{2/3}}{(M\,C_p)^3}\right]_{He}}$$

$$= \frac{\dfrac{44(0.72)^{2/3}}{(44 \times 0.27)^3}}{\dfrac{4(0.734)^{2/3}}{(4 \times 1.248)^3}} = 0.81$$

The above example shows that the expression $\dfrac{M(Pr)^{2/3}}{(M\,C_p)^3}$ can be very misleading in evaluating the merits of different gases. In the above example the difference amounts to a factor of approximately two. From equation (11) it can be seen that the required pumping power is proportional to the cube of the reactor output for a fixed reactor design and coolant. Thus, an increase by a factor of two in pumping power would increase the output of the system by about 26%. The actual reduction in pumping power of He compared to CO_2 is 1.51. By increasing the power input to the He by a factor of 1.51 the output of the system would be increased by about 15%.

NOMENCLATURE

A_c	Free flow cross-sectional area	ft^2
A_s	Heat transfer surface area	ft^2
C_p	Specific heat	Btu/lb ^oF
D_e	Equivalent diameter	ft
D_c	Channel diameter	ft
D_R	Fuel rod diameter	ft
f	Friction factor	
g	Conversion factor	ft lb/sec^2 lb
h	Heat transfer coefficient	Btu/sec ft^2 ^oF
ΔH	Heat loss	ft lb/lb
L	Length	ft
M	Molecular weight	lb/lb mol
N	Number of fuel elements in cluster	
P	Pressure	lb/ft^2 abs.
Pr	Prandtl Number	
Q	Heat transferred	Btu/sec
R	Universal gas constant	ft lb/^oR lb mol
Re	Reynolds Number	
T	Average temperature	^oR abs
V	Velocity	ft/sec
Δt_g	Gas temperature rise	^oF
Δt_w	Temperature difference from wall to gas	^oF
w	Weight flow	lb/sec
W_p	Wetted perimeter	ft

NOMENCLATURE (Continued)

W	Flow work	ft lb/sec
W_T	Total system flow	lb/hr
μ	Viscosity	lb/ft hr
ρ	Density	lb/ft^3

References

(1) "Army Mobile Power Plant", Sanderson and Porter, Report No. 1959-1.2, July 15, 1955.

(2) "Journal of the British Nuclear Energy Conference", 1956, Vol. 1, p 227.

(3) "Journal of the British Nuclear Energy Conference", 1957, Vol. 2, No. 2, p 226.

(4) "Gas-Cooled Power Reactor, Feasibility Study, Optimum Partially Enriched Uranium Nuclear Power Plant", Report No. 58-4-RE, March 1958.

(5) "The ORNL Gas-Cooled Reactor", ORNL-2500, April 1, 1958.

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