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HYDRAULIC DESIGN AND PERFORMANCE OF A GCFR CORE ASSEMBLY ORIFICE

by
I. M. TANG

MASTER

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ABSTRACT

The design and performance of a core assembly orifice for gas-cooled fast-breeder reactors (GCFRs) are studied in this report. Successful reactor operation relies on adequate cooling, among other things, and orificing is important to cooling. A simple, yet effective, graphical design method for estimating the loss coefficient of an orifice and its associated opening area is presented. A numerical example is also provided for demonstration of the method. The effect of the orifice configuration on orifice hydraulic performance is discussed. The design method stated above provides a first estimate toward an orifice design. Hydraulic experiments are required for verification of the design adequacy.

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1. INTRODUCTION

Orificing of fuel assemblies is commonly practiced in nuclear reactors. Sometimes a group of assemblies are orificed together. Often assemblies are orificed individually.

This study considers a simple, yet effective, graphical design method for sizing an orifice for a single assembly. Application of this method can easily be extended to a group of assemblies.

In determining the pressure drop of a reactor core, the reactor geometry and its needed flow rate for full power operation must be determined. This is normally achieved by optimum design studies based on the trade-offs of neutronics, thermodynamics, thermal-hydraulics, mechanical and material behavior, safety, and economics. The flow rate of an assembly is determined by the desired hot spot cladding temperature and the mixed mean outlet coolant temperature. For the maximum powered assembly, usually no orifice is provided. It, therefore, sets the required pressure drop across a reactor core. In a lesser powered assembly, a lesser flow rate is required to maintain the desired hot spot cladding temperature. Therefore, this assembly needs an orifice to maintain the same pressure drop set by the maximum powered assembly. Since adequate cooling is a key to successful nuclear reactor operation, it is obvious that the orifice function is important to reactor operations, although the orifice may seem to be a relatively simple device.

There are many types of orifices, varying in mechanical appearance and thermal-hydraulic performance. An orifice may be locked with a spring clamp, a screw-on device, and many other means. An orifice can be adjustable, permanently fixed, or removable. It can have a single hole or several apertures (like a baffled plate). However, all locking systems perform the same duty: restrict flow. Figure 1 (Ref. 1) illustrates a

(a)

Fig. 1. Typical orifice with a single hole (Ref. 1): (a) axial view
(sheet 1 of 2)

(b)

Fig. 1. Typical orifice with a single hole (Ref. 1): (b) radial cross-sectional view (sheet 2 of 2)

sharp-edged orifice. At General Atomic, the orifice design for the gas-cooled fast-breeder reactor (GCFR) is evolving. This figure is provided only for illustrative purposes and does not necessarily represent a fixed design.

2. A GRAPHICAL METHOD FOR SIZING AN ORIFICE

The total pressure drop of an assembly may be written as

$$\Delta P_{\text{core}} = \Delta P_i + \Delta P_b + \Delta P_o \quad , \quad (1)$$

where ΔP_i = pressure drop across the inlet portion, including inlet entrance contraction, inlet passage, and rod bundle entrance contraction;

ΔP_b = pressure drop across the fuel rod bundle; and

ΔP_o = pressure drop across the outlet portion, including rod bundle exit expansion, outlet passage, and outlet expansion.

The pressure drop across an orifice can be included in either ΔP_i or ΔP_o , depending on whether the orifice is located in the inlet or outlet portion of an assembly. ΔP_b is usually calculated from a rod bundle thermal-hydraulics code. Assuming that an orifice is in the outlet portion, then

$$\Delta P_o = K_o \frac{1}{2} \frac{\rho V^2}{g_c} \quad (2)$$

or

$$\Delta P_o = \frac{K_o}{A_o^2} \cdot \frac{1}{2} \frac{\dot{m}^2}{\rho g_c \cdot 144} \quad , \quad (3)$$

where ΔP_o = outlet pressure drop (psi),

ρ = coolant density

V = coolant velocity at the orifice throat,

$g_c = 32.2 \text{ lbm/lbf} \cdot \text{ft/sec}^2$,

A_o = orifice cross-sectional area (ft^2)

$\dot{m}$ = flow rate (lbm/sec), and

144 = conversion of ft^2 to in^2 .

Often, it is preferable to use Eq. 3 rather than Eq. 2, since $\dot{m}$ is a constant at steady-state condition at any assembly flow cross section.

To size the cross-sectional area of an orifice, Eq. 3 requires that its loss coefficient K_o be known. However, since K_o and A_o both are unknown in the equation, additional information must be provided to obtain the solution. A simple, yet effective, graphical method can be constructed for this solution.

2.1. THE GRAPHICAL METHOD

The additional information needed for solving Eq. 3 is the orifice coefficient distribution versus the Reynolds number. Figure 2 (Ref. 2) provides such information. The orifice flow coefficient C denoted in Fig. 2 is related to the loss coefficient by

$$K_o = \frac{1}{C^2} \quad . \quad (4)$$

Thus, a curve relating K_o and d_o/d_1 (or A_o/A_1) can be constructed given an operating Reynolds number. d_o and A_o are the orifice diameter and cross-sectional area, respectively, and d_1 and A_1 are the duct diameter and cross-sectional area adjacent to the orifice, respectively.* Knowing the desired orifice pressure drop ΔP_o , a curve can also be constructed for

* Data are also available from Ref. 3 for constructing this curve.

Flow Coefficient C for Nozzles⁷

Data from *Regeln fuer die Durchflussmessung mit genormten Duesen und Blenden* VDI-Verlag G m b H, Berlin, SNW, 7, 1937
Published as Technical Memorandum 952 by the NACA

$$C = \frac{C_d}{\sqrt{1 - \left(\frac{d_0}{d_1}\right)^4}}$$

Example: The flow coefficient C for a diameter ratio d_0/d_1 of 0.60 at a Reynolds number of 20,000 (2×10^4) equals 1.01

Flow Coefficient C for Square Edged Orifices^{7, 17}

$$C = \frac{C_d}{\sqrt{1 - \left(\frac{d_0}{d_1}\right)^4}}$$

$$C = \frac{C_d}{\sqrt{1 - \left(\frac{d_0}{d_1}\right)^4}}$$

Lower chart data from *Regeln fuer die Durchflussmessung mit genormten Duesen und Blenden* VDI-Verlag G m b H, Berlin, SNW, 7, 1937
Published as Technical Memorandum 952 by the NACA

Fig. 2. Orifice coefficients versus Reynolds number (reproduced from Ref. 2)

Eq. 3 based on the parametrically varied values of K_o and A_o . The solution for the desired K_o and A_o , therefore, must be the intersection of the two curves.

2.2. A NUMERICAL EXAMPLE FOR A SHARP-EDGED ORIFICE

A numerical example is demonstrated in this section with the desired flow conditions listed in Table 1. This example considers a sharp-edged orifice. Employing the method described above, the desired orifice loss coefficient K_o and its associated opening area A (and hence, its diameter) are obtained from Fig. 3. K_o and A are found to be 2.71 and 0.0375 ft^2 , respectively.

TABLE 1
ASSUMED DATA FOR A NUMERICAL EXAMPLE

Parameter	Description	Assumed Value
ΔP_o	Desired orifice pressure	12.75 psi
ρ	Helium density at 88 atm and 440°C	0.37 lbm/ft ³
A	Duct area adjacent to the orifice (a)	0.25 ft ²
d	Duct diameter adjacent to the orifice	0.5642 ft
Re	Reynolds number based on d	6×10^4

(a) This example considers a sharp-edged orifice.

Fig. 3. Graphical solution of a numerical example

3. ORIFICE CONFIGURATIONS AND PERFORMANCE VERSUS REYNOLDS NUMBER

An orifice can have a single-flow passage hole or multiple holes. The GCFR currently employs the single-hole design, which will be discussed in this section. An orifice can be of sharp-edge or round-nozzle construction. Figure 2 depicts the effect of the Reynolds number on orifice performance for both the sharp-edge and round-nozzle orifices.

It was noted in Section 2 that the orifice loss coefficient is equal to the inverse of the square of the flow coefficient or $K = 1/C^2$. Figure 2 shows that C increases as the Reynolds number decreases for a sharp-edge orifice, and the opposite effect is true for a round-nozzle orifice. Therefore, a sharp-edge orifice has less flow resistance during low flow conditions, a distinct reactor operations advantage.

The foregoing discussion strongly suggests that an orifice for a core assembly should possess a sharp-edge hole(s). It may also be interesting to investigate how corrosion and erosion round the sharp edge of an orifice throughout its in-core residence time. The subsequent alteration of the orifice performance may be investigated by out-of-pile experiments.

Whether to position an orifice at the core assembly inlet or outlet is another question. Equation 3 shows that the pressure drop of an orifice is inversely proportional to the coolant density ρ . At low flow conditions, especially when considering accident scenarios, the coolant temperature rise may be very large. As a consequence, ρ at an assembly outlet is much smaller than at an inlet. Hence, under these conditions, the orifice pressure drop ΔP is higher with the orifice placed at the outlet rather than at the inlet. The extent of this effect should be investigated by transient analyses of the reactor primary system under consideration.

4. HYDRAULIC EXPERIMENTS NEEDED

Design verification of the adequacy of pressure drop and flow requirements of an orifice must come from independent hydraulic experiments. As suggested by Eq. 3, orifice performance depends on its geometry (its size, sharp edge or not), mass flow rate (which is invariant at steady state), and the coolant temperature. In other words, an orifice generally does not remember the upstream events very well. For this reason, verification tests may be conducted with only a section of the flow duct immediately adjacent to the orifice (general performance tests). This procedure differs from the integrated whole assembly tests, which serve as the final verification process.

Thus, the experimental verification programs required may be conducted in two steps: (1) the general performance tests and (2) the integrated assembly tests. The general performance tests may be conducted with water (e.g., see Refs. 4 and 5).

Since the GCFR orifice design is not yet firm, it may be advantageous to conduct a series of parametric general performance tests which take into account the parameters of orifice opening size and Reynolds number (varying flow rate). This would provide a complete set of initial experimental data which would be useful for confirmation of adequate hydraulic performance due to any changes in orifice design. The integrated assembly tests will most likely be conducted with prototypic reactor operating conditions, since these tests are also intended for many other purposes.

5. CONCLUSIONS

A simple, yet effective, graphical design method for sizing an orifice for a GCFR core assembly has been presented above. The method employs the orifice pressure drop equation (Eq. 3) and a set of general orifice performance data found in literature (Fig. 2). The intersection of the two curves generated by the two sets of information sizes the opening area of the orifice and yields its loss coefficient. The numerical example provided in Section 2.2 demonstrates the simplicity in applying this method.

It was noted that the orifice loss coefficient decreases as the Reynolds number decreases (above Reynolds number 100) for a sharp-edged orifice. This important characteristic shows that a sharp-edged orifice has less flow resistance during low flow conditions where the Reynolds number may be in the range between ~ 400 to ~ 1000 . This is a distinct advantage for reactor operations. It is, thus, strongly recommended, on the basis of the above discussion, that a core assembly orifice should possess one or more sharp-edged holes. It may be of interest to investigate through out-of-pile experiments the hydraulic effect of rounding the sharp edge of an orifice by corrosion and erosion during normal operations. It was also suggested that it may be of advantage to place the orifice at the inlet rather than the outlet from a thermal-hydraulics point of view. During transient flow conditions, orifice pressure drop tends to be less sensitive to varying flow rate if the orifice were located at the inlet.

All reactor orifice designs must be verified by experiment. Adequate test results can be obtained by conducting some general performance hydraulic experiments, where only a section of the assembly flow duct is adjacent to and containing the orifice. Final verification can be obtained from the integrated whole assembly tests, which will also be used for other purposes.

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