NBS CIRCULAR 588

Determination and Correlation of Flow Capacities of Pneumatic Components

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The funetions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technieal problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers. These papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.25) and its Supplement ($0.75), available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Determination and Correlation of Flow Capacities of Pneumatic Components

D. H. Tsai and M. M. Slawsky

National Bureau of Standards Circular 588
Issued October 15, 1957

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.
Price 10 cents

Preface

The Pneumatics Laboratory was organized in 1951 at the National Bureau of Standards. Since that time, an important part of its work has been the evaluation and standardization of aircraft pneumatic components under the sponsorship of the Airborne Equipment Division of the Bureau of Aeronautics, Department of the Navy.

In the course of this work, it soon became evident that one of the serious difficulties in standardization and specification was the lack of an unambiguous method for defining the flow-handling capacity of pneumatic components. After considerable study and consultation with the industry, the Pneumatics Laboratory developed the concept of a "flow factor" for specifying the size of a component with respect to its capacity and for estimating pressure drops in pneumatic systems. The results of this study were reported at the 1952 New York Meeting of the Society of Automotive Engineers in a paper entitled A Method for Predicting Pressure Drops in Pneumatic Components and Systems, by M. M. Slawsky, M. Lutzky, and A. E. Schmidlin. The contents of this paper appeared in the Product Engineering Annual Handbook for 1955, published by the McGraw-Hill Book Co., Inc.

In October, 1954, in response to several hundred requests, the Pneumatics Laboratory revised the material described above and issued a report entitled Contributions to the Methods of Calculation and Measurement of Pressure Drop in Pneumatic Components and Systems, by M. M. Slawsky and R. C. Thompson. By the end of 1956 it was apparent that interest in the method of rating components described in this report had extended beyond aircraft use. The report, which was being distributed through the Bureau of Aeronautics, ceased to be an adequate means for disseminating this information. It was therefore decided that this Circular should be prepared and made available through the Government Printing Office.

As is often the case in making revisions, the original concepts have remained the same in principle, but have been changed in detail for the sake of improvement. The flow factor has been replaced by the "area factor". This area factor has the important advantages of being dimensionless and more precise. Those who have become familiar with the flow factor will recognize the area factor as being essentially the ratio of the flow factor of a component to the flow factor of the inlet port, or some other convenient reference area. A careful reading of this Circular will show that simplicity has not been sacrificed for precision. The choice of a convenient reference area and pressure ratio has been purposely left open. These should be determined by the users of components to suit their particular needs.

Charles W. Beckett, *Chief*
Thermodynamics Section.

Contents

Determination and Correlation of Flow Capacities of Pneumatic Components

D. H. Tsai and M. M. Slawsky [1]

Some of the problems of measurement and correlation of flow capacities of pneumatic components are discussed. A dimensionless "area factor," defined as the ratio of the "effective area" of the component to some reference area (equation 7), is introduced. The physical significance of the area factor and its experimental determination are discussed in some detail. Sample data are also included to show that this area factor provides a valid and convenient basis for comparing the flow capacities of components, regardless of their size and design, and over a wide range of test conditions.

1. Introduction

In the design and evaluation of a pneumatic component, one of the primary quantities of interest is the capacity of the device for handling flow with a given pressure drop across the component. To facilitate determination of this flow capacity, it is well to define the flow capacity in terms of conveniently measurable quantities such as pressure, temperature, and the mass rate of flow. Also, to facilitate comparison, it is useful to express the flow capacity in a dimensionless form. These considerations are then similar to those employed in defining the discharge coefficient of a flow-metering orifice. The purpose of this Circular is to discuss some of the problems connected with the determination and correlation of capacities of flow-handling devices. Special reference will be given to pneumatic components for aircraft application, in response to the many requests for information from the industry engaged in this area of engineering. But an effort will be made to emphasize the general features of the discussion, so that the considerations presented here could be applied, for the most part, to other flow-handling devices. Also, the discussion will be limited to the case of air flow in the component, but it is an easy matter to extend the discussion to other gases, by simply using the appropriate constants for the gas in question in the basic flow equations.

2. Discharge Coefficients of Nozzles and Orifices

2.1. Flow Through an Isentropic Nozzle

Before discussing the problems involved in the determination of the flow capacity of a pneumatic component, it is well to review briefly the basic ideas underlying the use of "discharge coefficients" for nozzles, orifices, and other flow-metering devices.

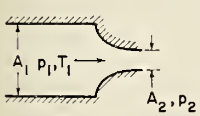

FIGURE 1. *Schematic nozzle and approach section.*

Consider a nozzle with an approach cross-sectional area A_1 and a throat (minimum) cross-sectional area A_2 (fig. 1). In the ideal case, if the flow through the nozzle is isentropic, the rate of flow under steady condition is given by

$$W_s = A_2 \frac{p_1}{\sqrt{T_1}} \left[\frac{2g}{R} \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{r^{2/\gamma} - r^{(\gamma+1)/\gamma}}{1 - r^{2/\gamma}(A_2/A_1)^2} \right]^{1/2}. \quad (1)$$

where

W_s = mass rate of flow through the isentropic nozzle, lbm/sec (lbm = pound mass).
A_1 = cross-sectional area of approach section to nozzle, in.^{2}
A_2 = cross-sectional area at throat of nozzle, in.^{2}
p_1 = pressure in approach section, psia.
p_2 = pressure in throat section, psia.
T_1 = temperature in approach section, °R.
g = dimensional constant = 32.2 lbm-ft/lbf-sec^2 (lbf = pound force).
R = gas constant = 53.3 lbf-ft/lbm-°R for air.
γ = ratio of specific heat at constant pressure to that at constant volume = 1.4 for air and diatomic gases.
$r = p_2/p_1$ = ratio of pressure at the throat to the pressure in the approach section.

[1] Present address: Combustion Dynamics Division, Air Force Office of Scientific Research, Washington 25, D. C.

The term $[1-r^{2/\gamma}(A_2/A_1)^2]^{1/2}$ is sometimes called the approach velocity factor. Since r is never greater than unity, this factor is very nearly equal to unity when A_1 is large compared to A_2. For example, if $A_1=10A_2$, a maximum error of only 0.5 percent would result if this factor were replaced by unity. Also, with a larger approach section A_1, the velocity in the approach section is lower, and the measurement of p_1 and of T_1 both become easier. For these reasons, it is desirable to keep A_1 large compared to A_2. Equation (1) then simplifies to

$$W_s=A_2\frac{p_1}{\sqrt{T_1}}\left[\frac{2g}{R}\cdot\frac{\gamma}{\gamma-1}\left(r^{2/\gamma}-r^{(\gamma+1)/\gamma}\right)\right]^{1/2}. \qquad (2)$$

or

$$W_s=A_2\frac{p_1}{\sqrt{T_1}}\Phi(r), \qquad (3)$$

with

$$\Phi(r)=\left[\frac{2g}{R}\cdot\frac{\gamma}{\gamma-1}\left(r^{2/\gamma}-r^{(\gamma+1)/\gamma}\right)\right]^{1/2}. \qquad (4)$$

For a diatomic gas, $\gamma=1.4$, and $\Phi(r)$ reaches a maximum value of 0.532 lbm-$\sqrt{°\mathrm{R}}$/lbf-sec when r is equal to 0.528. At this point, sonic velocity is reached in the throat of the nozzle, and further lowering of the downstream pressure would not increase the flow rate W_s. Therefore, $\Phi(r)$ remains at 0.532 for values of r smaller than 0.528. Figure 2 shows the relationship between $\Phi(r)$ and r.

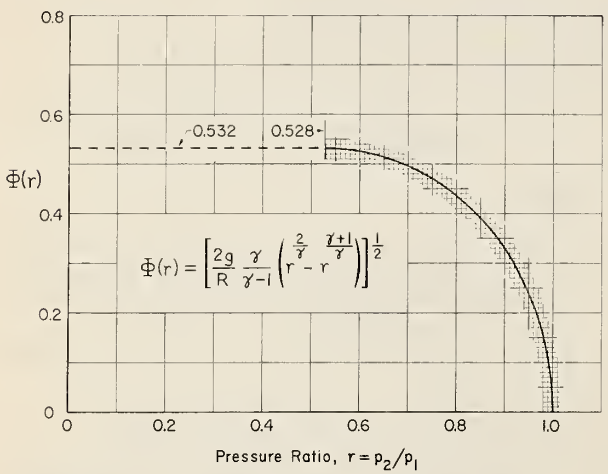

FIGURE 2. *Values of $\Phi(r)$ versus r for air, $\gamma=1.4$.*

2.2. Discharge Coefficient of a Nozzle

The actual flow rate through a nozzle is smaller than that given by eq (3) (under the same conditions of p_1, T_1, and r) because of friction between the fluid and the wall of the nozzle. In describing the flow characteristics through an actual nozzle, it is convenient to define the term "discharge coefficient" as the ratio of the actual flow rate W to the isentropic flow rate W_s:

$$C=\frac{W}{W_s}=\frac{W}{A_2(p_1/\sqrt{T_1})\,\Phi(r)}. \qquad (5)$$

The discharge coefficient C is a function of the Reynolds number based on the diameter of the throat. But if the flow is in the turbulent regime (high Reynolds number) as in many engineering applications, the variation in C with Reynolds number is small (see further discussion of this point in section 3). Thus, except where high precision is important, as in flow-metering work, the value of C may be taken as constant, so that once the value of C is determined for one flow rate, the pressure-flow relationship is known fairly accurately over a wide range of flow conditions. C is convenient also for comparing the capacities of nozzles of different designs and sizes, because the isentropic flow rate provides a valid reference flow rate which is easily computed, and because the discharge coefficient itself is independent of the size of the nozzle for the purpose here discussed.

2.3. Discharge Coefficients of Other Flow-Metering Devices

The above considerations on the use of discharge coefficients for nozzles could be applied to other flow-handling devices. The reference flow rate could still be taken as the isentropic flow rate through some "equivalent" nozzle. But, except in the simplest cases in which the minimum area in the flow device could be clearly identified, there would be some question as to the proper choice of the throat area of the equivalent nozzle. Moreover, because the flow patterns would not be the same, some question would arise, also, as to the measurement of the corresponding pressures p_1 and p_2 in the flow device and in the nozzle. Therefore, the discharge coefficient of a flow device would generally depend on the choice of the minimum area and the location of the pressure taps, and would probably vary somewhat with the pressure ratio, as well as with the Reynolds number, as was mentioned earlier. For example, the discharge coefficient of a sharp-edged orifice may vary from 0.6 at very low flow rates to around 0.85 at very high flow rates.[2] For these reasons, in flow-metering work the construction of the flowmeter, the location of the pressure taps, and the range of test all must be carefully specified and standardized along with the discharge coefficient obtained experimentally at each Reynolds number.

[2] See J. A. Perry, Jr., Critical flow through sharp-edged orifices, Trans. ASME **71**, 757, figure 7 (1949).

3. Area Factor of a Flow Component

3.1. Effective Area A_{eff}

The foregoing discussion indicates that the flow characteristics of different components may be compared on the basis of their discharge coefficients only if some arbitrary method is first adopted for specifying the minimum (throat) area and the locations of the pressure and the temperature probes. This is difficult because flow components are generally different in geometry and design. But for the minimum area, the difficulty may be avoided by combining the flow coefficient with the minimum area into some "effective area" so that

$$A_{\mathrm{eff}}=CA_2=\frac{W}{(p_1/\sqrt{T_1})\Phi(r)}. \tag{6}$$

A_{eff} is then a fictitious area equal to the ratio of the actual rate of flow W, measured under the conditions p_1, T_1, and r, to the quantity $(p_1/\sqrt{T_1})\Phi(r)$, which is the rate of flow through an isentropic nozzle of unit area, under the same conditions. Or, alternatively, A_{eff} may be considered also as the throat area of a fictitious isentropic nozzle that would pass flow at the rate of W under the conditions of p_1, T_1, and r.

3.2. Measurement of p_1, T_1, and p_2

Regarding the conditions of test, the problem is to specify where p_1, T_1, and p_2 should be measured in the actual component. Ideally, these quantities should correspond to those in the isentropic nozzle, i.e., p_1 and T_1 should be the pressure and temperature, respectively, in the approach section, and p_2 should be the pressure at the throat. However, because of the differences in the flow patterns, it is usually not possible to have exact correspondence in the pressures and temperatures. Also, from a practical point of view, it may not be possible to locate pressure and temperature probes in the actual component without altering the component in some manner. For these reasons, it is preferable not to insist on exact correspondence, but to specify other pressures and temperatures which could be measured more easily at stations immediately upstream and downstream of the component. This would be consistent, also, with the idea of using the effective area, which ignores the details of the flow inside the component, but treats the whole component as some equivalent isentropic nozzle with an effective throat area of A_{eff}. But A_{eff} determined this way in general would not remain constant at all flow rates, as is the case with an isentropic nozzle, but would vary somewhat with the pressure ratio across the component. It is usually necessary, therefore, to specify the pressure ratio along with each value of A_{eff}.

If this point of view is adopted, then the problem is to specify the stations for measuring pressure and temperature so that, as far as possible, they would have comparable meaning for components of different designs and sizes. Because the fluid velocity upstream of the component depends on the size of the line that is not a part of the component, and because this velocity is usually not negligible, account must be taken of the velocity of approach to the component. The velocity could be determined by means of anemometers or by measurement of the stream (static) pressure, p_1, and the isentropic stagnation pressure. But these methods would be difficult to apply if the line and the component are both small. A simpler and more reproducible scheme is to use a large approach section with a nozzle-shaped transition section joining the approach section and the component, and to take the static pressure in the approach section as p_1. With this scheme, the large approach section justifies replacing the approach velocity factor with unity, as in eq (2) and (5), whereas the nozzle-shaped transition section minimizes the entrance loss (to the component), which is not properly attributable to the component. The low velocity in the approach section also makes the measurement of the temperature T_1 easier and perhaps somewhat more accurate.

The pressure p_2 logically should be taken as the static pressure at the exit plane of the component. For actual measurement, however, it is more convenient to have the component discharge into a larger pipe connected to the component through an abrupt change of section, and to take p_2 as the pressure in the dead-air region near the exit of the component. This pressure is very nearly equal to the pressure at the exit plane if the flow through the component is below the choking level. The advantage of measuring the pressure in the dead-air region is that the fluid velocity in this region is much lower than at the component exit, and, therefore, small variations in the location and construction of the pressure tap would not affect the pressure measurement. When the flow is increased to the choking level (by lowering the pressure in the larger pipe) the pressure at the exit plane of the component may be appreciably different from the pressure in the dead-air region. But, because the flow rate is now independent of the downstream pressure, p_2 could still be taken as the pressure in the dead-air region without giving rise to any ambiguity.

3.3. Area Factor and Choice of Reference Area

In order to facilitate comparison of components of different designs and sizes, it is convenient to define a dimensionless "area factor" equal to the ratio of the effective area A_{eff} to some reference area A_p:

$$\text{area factor} = A_F = \frac{A_{eff}}{A_p} = \frac{W}{A_p(p_1/\sqrt{T_1})\Phi(r)} \quad (7)$$

The last relationship shows that the area factor is also the ratio of the actual rate of flow through the component to the isentropic rate of flow through an area A_p, with both flow rates measured under the same conditions of p_1, T_1, and r.

The choice of the reference area is somewhat arbitrary and depends largely on the information one wishes to obtain from the area factor. For example, in the schematic poppet valve mechanism of figure 3, an area factor based on A_2 would be convenient for comparing the effect of changing the configuration (shape and seat angle) of the poppet valve. But an area factor based on either A_1, or maximum A_2 (poppet valve in position b), or even A_3, would be more meaningful for indicating the capacity of the component as affected by the position of the poppet valve. In fact, A_1 is the area that will ultimately limit the capacity of the component. Area A_4 also may be a meaningful reference area under certain conditions. For example, if A_4 were fitted with a piston, figure 3 would be similar to the inlet side of a reciprocating compressor or internal combustion engine. In both cases, the quantity A_{eff}/A_4 is a very useful parameter for correlating air flow data.

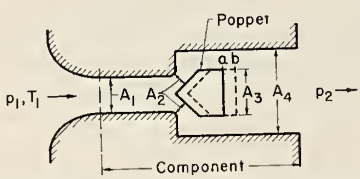

Figure 3. *Schematic poppet valve mechanism showing several areas, any one of which could be used as a reference area.*

3.4. Effect of Reynolds Number

It was stated earlier that the effect of fluid friction on the value of discharge coefficient (or area factor) would be small if the flow is in the turbulent regime. In the case of flow through a well-shaped nozzle, Rivas and Shapiro [1] [3] showed that if the initial turbulence of the stream is low, transition to turbulent flow would occur, for example, at one-half diameter inside the parallel portion of the throat, if the diameter Reynolds number, Rey_D, is of the order of 2×10^5. Here Rey_D is defined as

$$\text{Rey}_D = \frac{\rho u D}{\mu},$$

where ρ is the mass density, u the velocity, μ the viscosity of the fluid, and D is the diameter of the throat. For Rey_D greater than 2×10^5, the data in [1] showed that the maximum variation in the discharge coefficient of the nozzle is less than 1 or 2 percent. Similar results were reported by Bean, Johnson, and Blakeslee [2], and other investigators.

The above criterion for transition to turbulent flow may be conveniently applied to the present discussion. This would be especially valid if a nozzle-like adaptor is placed immediately upstream of the component under test. Under these conditions, it may be shown that a diameter Reynolds number of 2×10^5 is easily reached, even in very small components, such as those of the "dash 4" series for aircraft application [3]. For these components, the reference area may be taken as the cross-sectional area of the inlet port. Using a "dash 4" component as an example, the reference area based on the nominal inlet port diameter of 0.172 in. is 0.0233 in.^{2} If the area factor of the component is unity, the mass rate of flow would be

$$W = (0.0233)\frac{p_1}{\sqrt{T_1}}\Phi(r) \text{ lbm/sec.}$$

By continuity relationship, $W = \rho u A$, so that

$$\rho u \frac{0.0233}{144} = (0.0233)\frac{p_1}{\sqrt{T_1}}\Phi(r),$$

or

$$\rho u = 144\frac{p_1}{\sqrt{T_1}}\Phi(r) \text{ lbm/ft}^2\text{ sec.}$$

The diameter Reynolds number is therefore

$$\text{Rey}_D = \frac{\rho u D}{\mu}$$

$$= \frac{144}{\mu}\frac{0.172}{12}\frac{p_1}{\sqrt{T_1}}\Phi(r).$$

If $p_1 = 100$ psi, $T_1 = 520°$ R, and $\mu = 12\times10^{-6}$ lbm/ft-sec for air, and if $\Phi(r)$ is taken as 0.532 lbm-$\sqrt{°\text{R}}$/lbf-sec for choking flow, then

$$\text{Rey}_D = \frac{144}{12\times10^{-6}}\frac{0.172}{12}\frac{100}{\sqrt{522}}(0.532)$$

$$= \frac{17.2}{22.8}(0.532)(10^6) = 4\times10^5.$$

Thus, even with an area factor of 0.5, the transition to turbulent flow would have taken place a short distance (one-half diameter of the inlet port) from the entrance to the component. If the area factor were still smaller, a higher pressure could be used to keep Rey_D at the same value. Under these conditions, then, the effect of Reynolds number would indeed be small and therefore negligible.

[3] Figures in brackets indicate the literature references at the end of this Circular.

In summary, the above discussions give some idea of the effect of Reynolds number on the area factor, and the conditions under which this effect is small. Fortunately these conditions are encountered in many engineering applications, so that ordinarily the effect of Reynolds number need not be considered. It would be well, however, to check the value of Reynolds number under extreme conditions, and to make suitable adjustments if the Reynolds number should be too low.

3.5. Capacity Rating of a Component

In the foregoing paragraphs, various aspects of the general problem of determining the capacity of flow components have been discussed. If it is now desired to express the capacity numerically in terms of some effective area or area factor, further specifications on the experimental apparatus and method of test must be stipulated. These specifications should include details on the construction of the test sections, the locations of temperature and pressure taps, the geometry of the transition section between the upstream approach section and the component, the method of selecting the reference area A_p, as well as other pertinent details. Also, because the area factor will, in general, vary with the pressure ratio across the component (see discussion of variation of discharge coefficient of an orifice with pressure ratio), the pressure ratio must also be specified along with each value of the area factor.

These are general considerations. The detailed specifications are primarily a matter of formulating appropriate codes and standards for testing, similar to the standardization of flowmeters mentioned earlier. It is beyond the scope of the present discussion to propose such a set of standards. For the purpose of this Circular, it may be of greater interest to discuss some of the general design features of a test setup that would be suitable for measuring the capacity of a flow component.

4. Experimental Measurement of Area Factor

4.1. Design Considerations for Experimental Setup

Figure 4 shows a schematic diagram of a "typical" experimental setup for measuring the flow through a component. High-pressure air in a continuous supply enters the system through the main valve. As the flow passes through the pressure regulator and enters the approach section, its pressure is reduced to the desired level p_1, which is adjustable by the setting of the pressure regulator. From the approach section the flow passes through a nozzle-shaped transition section into the component, and thence into the exit section, where the pressure p_2 is measured. The flow rate is controlled by means of the control valve at the end of the exit section, and measured by the flowmeter connected to the control valve, at the end of the system.

The above is only one of several possible arrangements for measuring the flow through a component. In some cases, for example, it may be desirable to pressurize the flowmeter by placing an additional control valve downstream of the flowmeter. Or, if a suction pump is used instead of pressurized air, atmospheric conditions could be taken as the upstream conditions, so that the approach section (above the transition section) could be eliminated altogether. The choice of a particular system depends on the component under test as well as the equipment available. The important considerations are that the pressure and temperature measured at stations upstream and downstream of the component should be as far as possible comparable from one component to another, and that the measurement of flow rate should be accurate.

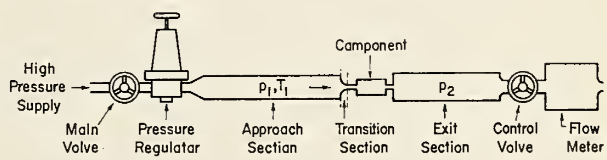

FIGURE 4. *Typical experimental setup for measuring flow capacity.*

To ensure maximum accuracy in the measurement of p_1 and p_2, the approach and exit sections should be smooth and straight, and long compared to their diameters. In an orifice meter installation [4], if the upstream section is preceded by a regulator, and the downstream section followed by a control valve, as in figure 4, the length of the upstream section should be at least 20 times the diameter of the upstream section, and the length of the downstream section should be at least 5 or 6 times the diameter of the downstream section. These lengths are specified for pressure taps placed close (within one pipe diameter) to the orifice plate, and applies to orifice meters in which the upstream pipe diameter (usually the same as the downstream pipe diameter) is at least 3 times the diameter of the orifice. If the pressure taps are placed farther upstream and downstream, or if the upstream pipe diameter is less than 3 times the orific diameter, increased upstream and downstream lengths are recommended [4]. In the absence of more detailed information on the test setup for the component, the recommended practice for orifice meter installation, including the construction and location of pressure and temperature taps, may be conveniently adopted.

4.2. Flowmeters

The selection of flowmeters depends on the range of flow rates the test setup is called on to measure. For a component of a given size, the flow rate under any given set of test conditions may be estimated from eq (7) if the approximate value of the area factor of the component is known. Once the range of the maximum and minimum flow rates is determined, a suitable flowmeter can usually be selected from the literature on the subject. However, if the range is very large, several flowmeters, each covering a portion of the range, may have to be used. Therefore, some flexibility in the test setup should be given careful consideration at the design stage, especially if the same setup is to be used for measuring components of several sizes. The same consideration also applies to the selection and installation of the control valve.

Except for leakage type of flow, the flow through a component is usually in a range high enough so that the flow rate can be measured by means of an orifice type or a nozzle type of flowmeter. These are convenient to use because of their simplicity, and because of the large amount of data that has been compiled in the literature. Generally speaking, the orifice type is somewhat less expensive than the nozzle type, but has a smaller capacity than the latter. The choice between the two types depends primarily on the requirements of the test setup.

The transition section joining the approach section and the component should be smooth and well shaped to reduce entrance loss to the component. But for the purpose of standardizing test equipment, it may be more important to adopt an easily reproducible shape, such as a rounded section with a single radius, than to have a highly efficient shape with minimum loss. It is also important to have an accurate throat diameter in the transition piece if the reference flow is to be based on the cross-sectional area of the throat. If the area factor of a component is to be measured, for example, the throat diameter should be very nearly equal to the nominal inlet port diameter of the component.

The diameter of the approach section should be 3 or 4 times the diameter of the throat in the transition section in order to take advantage of the fact that the approach velocity factor would then become negligible, as pointed out earlier. If the test setup is to be used for measuring components of several sizes, the diameter of the approach section should be made large enough to accommodate the largest component.

Regarding the installation of either type of flowmeter, it is perhaps most convenient to have the flowmeter at the end of the test setup, as in figure 4, so that the differential pressure across the flowmeter can be measured with a simple manometer. The useful range of the flowmeter could be increased somewhat by pressurizing the flowmeter by means of a control valve downstream of the flowmeter.

4.3. Sample Test Data

The various points brought out in the discussion of the area factor and its measurements may be further clarified by examining representative test data such as those shown in figure 5. These data were obtained by measurements on a group of four components in two sizes, two in each size. The nominal inlet port diameter was 0.172 in. (inlet port area=0.0233 in.^{2}) for the smaller components, and 0.297 in. (inlet port area=0.0693 in.^{2}) for the larger components. The components of the same size were identical within manufacturing tolerances, but in the two sizes, these components were not geometrically similar. In fact, the ratios of the dimensions of the corresponding parts and flow passages were found to vary from 1 to 2 to about 1 to 1, and the majority of them were greater than the ratio of the inlet port diameters, which was 0.172/0.297, or 0.58.

The test setup used for measuring the flow rate was similar to the one shown schematically in figure 4. The upstream pressure was regulated by means of a pressure regulator connected to a 3,000-psi high-pressure source.

The diameter (i.d.) of the approach section was 1½ in., giving a cross-sectional area of 1.77 in.^{2} This was 25 times as large as the inlet port of the large components, and over 75 times as large as that of the small components. The approach velocity factor, therefore, could be neglected without appreciable error. The approach section was approximately 24 diameters long. The pressure and temperature probes were both 2½ diameters upstream of the component, at the end of the approach section. The temperature probe per-

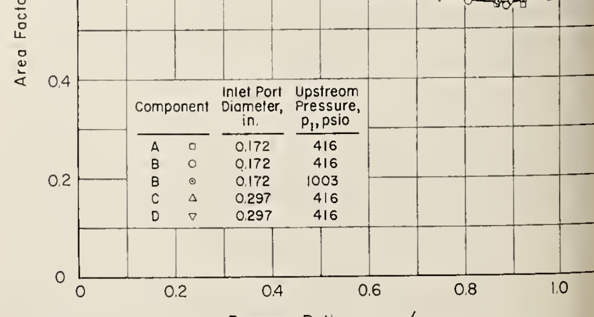

FIGURE 5. *Sample test data showing good correlation on the basis of area factor.*

haps could have been located farther upstream to reduce disturbance in the flow just ahead of the component, but this was not investigated.

The transition section connecting the approach section and the component was nozzle-shaped with a throat diameter equal to the nominal inlet port diameter of the component. The cross-sectional contour from the entrance plane to the throat section was a simple quarter-circle, with a radius equal to ½ in.

The component discharged into the exit section through a sudden expansion from the diameter of the outlet port to the full diameter of the exit section, which was 1¾ in. The exit section was approximately 13 diameters long, and the pressure tap was approximately 8 diameters downstream of the component.

The flow meter was of the nozzle type built to the specifications of reference [5]. The flow rate was computed from the data given in reference [6], which was a revision of reference [5]. According to reference [6], the accuracy of the flow measurement was somewhat better than 1 percent.

The procedure for the test was straightforward. The pressure regulator was first adjusted to give the desired pressure in the approach section. The control valve was then opened to some arbitrary position to permit some air to flow through the component. The pressure regulator was then readjusted, as necessary, to make sure that the pressure in the approach section was at the desired level. The measured quantities were: Pressure and temperature in the approach section, pressure in the exit section, pressure and temperature in the flowmeter, and the barometric pressure. The rate of air flow was determined from the last three items of information. The area factor was then computed from eq(7), using the cross-sectional area of the inlet port as the reference area. This process was repeated at other settings of control valve, until a range of pressures in the exit section was covered.

The experimental results obtained in this manner were plotted in figure 5. The correlation on the basis of area factor is seen to be very good with respect to changes both in upstream pressure and in the size of the inlet port. In addition, since no effort was made to control the upstream temperature, which was observed to vary as much as 30° F from room temperature in a single series of tests, these results show that the area factor also provides a basis for correlating the effect of changing the upstream temperature. It is also interesting to note that the area factor was not constant, but increased to a maximum with decreasing pressure ratio (except for the small initial drop at pressure ratio near 1.0). The maximum was reached at a pressure ratio of about 0.4, somewhat lower than the critical pressure ratio of 0.528 for air flow through an isentropic nozzle. Below 0.4, the area factor remained constant, indicating that the flow was choked. The variations in area factor with pressure ratio observed here are typical of components in which the flow passage is not of the simple nozzle type. In specifying the capacity of a component, it is therefore necessary to give both the area factor and the corresponding pressure ratio across the component.

In conclusion, the data of figure 5 show that good correlation in terms of area factor versus pressure ratio was obtained over a wide range of size and test conditions. This good correlation resulted, of course, from the fact that the flow patterns in the test components were basically similar. In general, the area factor curves for dissimilar components will be different from one another. But, whether the components are similar or not, it is clear from the example given here that the area factor, obtained in a certain prescribed manner, provides a valid and convenient basis for comparing the capacities of flow components, regardless of their size and design, and over a wide range of test conditions.

5. References

[1] M. A. Rivas, Jr., and A. H. Shapiro, On the theory of discharge coefficients for round-entrance flowmeters and venturis, Trans. ASME **78**, 489–497 (1956).

[2] H. S. Bean, R. M. Johnson, and T. S. Blakeslee, Small nozzles and low values of diameter ratio, Trans. ASME **76**, 863–871 (1954).

[3] Air Force-Navy aeronautical design standard, Fitting end, standard dimensions for flared tube connection and gasket seal, Drawing AND 10056 (U. S. Government Printing Office, Nov. 10, 1954).

[4] R. F. Stearns, R. R. Johnson, R. M. Jackson, and C. A. Larsen, Flow measurement with orifice meters, p. 105–112 (D. Van Nostrand Co., Inc., New York, N. Y., 1951).

[5] C. L. Sadler and J. Hulman, Air flow orifices for use in determining air flow during the tests of air pumps, Air Corps Tech. Rept. No. 4552 (addendum No. 1 to 4409) (Central Air Documents Office, Wright-Patterson Air Force Base, Dayton, Ohio, July 15, 1940).

[6] A. Evans and W. H. Hynes, Air flow orifices for use in determining air flow during tests of air pumps, Army Air Forces Technical Report No. 4552, rev. I (Central Air Documents Office, Wright-Patterson Air Force Base, Dayton, Ohio, March 4, 1946).

WASHINGTON, May 23, 1957.

U. S. GOVERNMENT PRINTING OFFICE: 1957

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its headquarters in Washington, D. C., and its major field laboratories in Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D. C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Nuclear Physics. Radioactivity. X-rays. Betatron. Nucleonic Instrumentation. Radiological Equipment. AEC Radiation Instruments.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Specifications. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

- Office of Basic Instrumentation
- Office of Weights and Measures

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Calibration Center. Microwave Physics. Microwave Circuit Standards.

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA