SAE Aerospace
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AEROSPACE INFORMATION REPORT

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Method of Evaluating Pneumatic Ground Power Units

1. SCOPE:

This SAE Aerospace Information Report (AIR) covers, and is restricted to, the behavior of air under conditions of critical and subcritical flow at temperatures less than 500 °F.

1.1 Purpose:

This AIR is intended to provide basic information and theoretical background on proper types of test equipment and calculation procedures for use in measuring air in critical and subcritical flow conditions, as are usually encountered in jet engine starting applications.

2. APPLICABLE DOCUMENTS:

2.1 This AIR should be supplemented by the following document:

ASME MFC-3M-1989, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi

2.2 Other Publications:

Loomis, A. W., ed., Compressed Air and Gas Data, Third Edition, NJ:Ingersoll-Rand, 1980

Hotchkiss, R. M., Accessory Controls & Equipment Corp., Critical Flow Orifices for Flow Restriction and Measurement, Windsor, CT, 1989

American Society of Mechanical Engineers, ASME MFC-3M-1989, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi, NY:ASME, 1990

3. THE FLOW MEASUREMENT DEVICE:

Two basic types of flow measurement devices have historically been employed in the measurement of flows of air, namely the orifice and the quarter-elliptical nozzle. It is important to note that, as a primary flow measuring device, the orifice plate is subject to a number of restrictions on surface flatness, roughness, edge thickness, etc.[1] An orifice strictly conforming to these requirements will provide a discharge coefficient of 0.61 fairly constantly.

Experience indicates that the most important factor is the "sharp edge" of the orifice and that burrs on the edge can reduce the coefficient, and rounding of the edge due to wear or the buildup of dirt can increase the coefficient to as much as 0.8[2]. Since the coefficient is a direct multiplier in the equation for mass flow through an orifice[3], this variation can yield large errors. It is, therefore, recommended that the orifice not be applied as a primary measuring device. The orifice can, however, be successfully applied as a restricting device, in order to model a particular aircraft system, if an accurate flow measuring device is also employed.

The ASME low beta ratio flow nozzle is designed with an elliptical shape[4]. The controlling assumption is that there is little velocity in the tube to which the nozzle is attached and thus P_v (velocity pressure) is at a minimum and P_s (static pressure) = P_t (total pressure). Since tube diameter is $\geq$4 times nozzle diameter, tube area $\geq$16 times nozzle area, and thus nozzle velocity pressure $\geq$256 times tube velocity pressure. This leaves tube velocity pressure as an insignificant factor (<0.5%). The smooth shape of the ellipse converts virtually all of the P_s (static pressure) into velocity at the nozzle outlet. For nozzles 2 inch diameter or greater, the flow coefficient is 0.985 or greater[5], thus providing accuracy in the range of ±1.5%.

Thus, the preferred apparatus utilizes an orifice as a restricting device to model the load (aircraft) while a flow nozzle is used to accurately measure the flow rate.

4. CALCULATIONS FOR ORIFICE SELECTION:

Normal rates of flow encountered in jet starting applications, when flowed through an orifice to simulate the pressure drop of an aircraft system normally result in the condition of critical flow i.e., the velocity of the air reaches the speed of sound. The calculation procedures detailed below are valid within the following limitations:

a. The medium is air at temperatures below 500 °F.
b. The airflow rate is fully developed critical flow. For critical flow to exist, the absolute pressure downstream of the orifice (P2) must be less than 0.5 times the upstream pressure (P1)[6].

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1 ASME, MFC-3M-1989 (NY, NY, 1990), 21-23.
2 Loomis, A. W., ed., Compressed Air and Gas Data, Third Edition (NJ:Ingersoll-Rand, 1980), 5.13.
3 Ibid., 5.14.
4 ASME MFC-3M-1989, 33.
5 ASME MFC-3M-1989, 35.
6 Loomis, op.cit., 5.11.

4. (Continued):

The basic equation for critical flow through an orifice is:

$$W = (0.53)(P1)(A)(C)/(T1)^{0.5} \quad \text{(Eq.1)}$$

where:

W = mass flow, lb/s
P1 = upstream pressure, psia
A = area of orifice, in^2
C = flow coefficient of orifice
T1 = upstream temperature, °R[7]

Equation 1 may be reduced for convenience to:

$$W = (24.9757)(P1 + 14.696)(d^2)(C)/(T1 + 460)^{0.5} \quad \text{(Eq.2)}$$

where:

d = orifice diameter, in
P1 = upstream pressure, psig
T1 = upstream temperature, °F

Equation 2 may be used to select an orifice size, for use as a restricting device, to simulate an appropriate system for a test apparatus (provided that the limits detailed above are observed).

The flow equation can be broken down and adjusted into a nomograph, presented as Figure 1[8]. This nomograph makes orifice sizing extremely easy. Since the nomograph is specifically written to the application of jet engine starting, it is limited to cover:

a. Flows (W) to 300 lb/min
b. Air temperatures (T1) of -100 to 500 °F
c. Upstream pressures (P1) of 25 to 45 psig

5. CALCULATION OF MASS FLOW THROUGH AN ASME LOW BETA RATIO NOZZLE:

All flow through the test duct and nozzle will be in the subcritical range and the nozzle should be mounted on an appropriate test duct as specified in ASME MFC-3M-1989 section 8.3 in order to meet the assumptions detailed in Section 3 of this document. In addition, experience has shown that nozzle size must be selected to maintain a total pressure in the duct of at least 30 in H_2O in order to maintain a uniform flow profile and insure accuracy.

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7 Loomis, op.cit., 5.14

8 Hotchkiss, R. M., Accessory Controls & Equipment Corp., Critical Flow Orifices for Flow Restriction and Measurement (Windsor, CT, 1989).

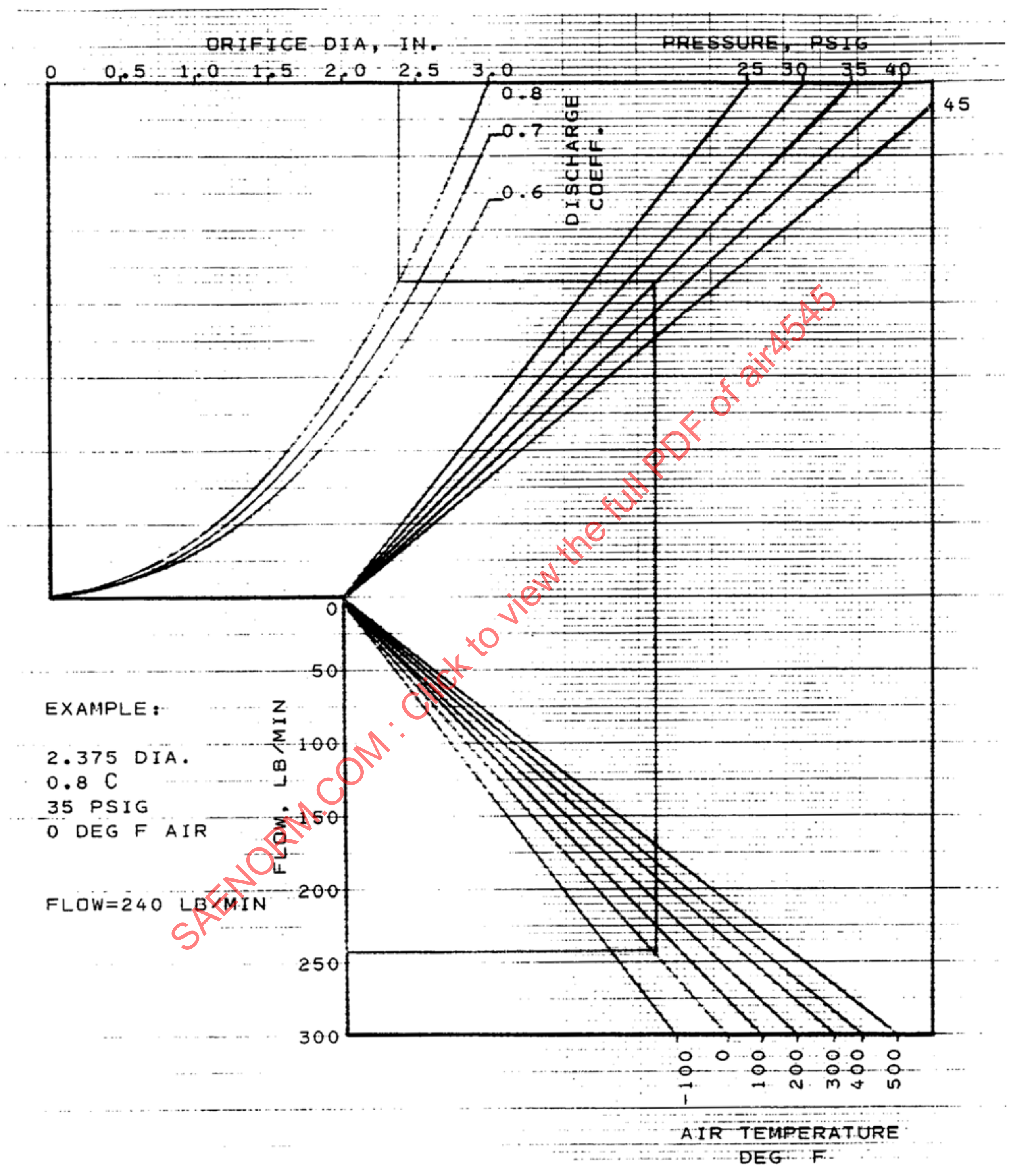

FIGURE 1 - Orifice Selection Nomograph