EREST

s
ings

ions

g Engineering

ndamentals
plications

s

ng Handbook

PUMP HANDBOOK

EDITED BY

Igor J. Karassik
William C. Krutzsch
Warren H. Fraser
Worthington Pump Inc.

Joseph P. Messina
Public Service Electric and Gas Company
New Jersey Institute of Technology

SECOND EDITION

McGRAW-HILL BOOK COMPANY

New York St. Louis San Francisco Auckland Bogotá
Hamburg London Madrid Mexico
Montreal New Delhi Panama Paris São Paulo
Singapore Sydney Tokyo Toronto

The term *jet pump*, or *ejector*, describes a pump having no moving parts and utilizing fluids in motion under controlled conditions. Specifically, motive power is provided by a high-pressure stream of fluid directed through a nozzle designed to produce the highest possible velocity. The resultant jet of high-velocity fluid creates a low-pressure area in the mixing chamber, causing the suction fluid to flow into this chamber. Ideally, there is at this point an exchange of momentum that produces a uniformly mixed stream traveling at a velocity intermediate between the motive and suction velocities. The diffuser is shaped to reduce the velocity gradually and convert the energy to pressure at the discharge with as little loss as possible. The three basic parts of any ejector are the nozzle, the diffuser, and the suction chamber, or body (Fig. 1).

DEFINITION OF TERMS

A definition of standard ejector terminology is as follows:

Ejector General name used to describe all types of jet pumps which discharge at a pressure intermediate between motive and suction pressures

Eductor A liquid jet pump using a liquid as motive fluid

Injector A particular type of jet pump which uses a condensable gas to entrain a liquid and discharge against a pressure higher than either motive or suction pressure; principally, a boiler injector

Jet compressor A gas jet pump used to boost pressure of gases

Siphon A liquid jet pump utilizing a condensable vapor, normally steam, as the motive fluid

Of concern to this text are jet pumps used to pump liquids. Eductors, being the most common, will receive the principal treatment herein. Sizing parameters for siphons will also be presented.

EDUCTORS

Theory and Design Eductor theory is developed from the Bernoulli equation. Static pressure at the entrance to the nozzle is converted to kinetic energy by permitting the fluid to flow freely through a converging-type nozzle. The resulting high-velocity stream entrains the suction fluid in the suction chamber, resulting in a flow of mixed fluids at an intermediate velocity. The diffuser section then converts the velocity pressure back to static pressure at the discharge of the eductor.

The Bernoulli equation for the motive fluid across the nozzle of an eductor is

$$\frac{P_1}{\gamma_1} + \frac{V_1^2}{2g} = \frac{P_s}{\gamma_1} + \frac{V_N^2}{2g} \tag{1}$$

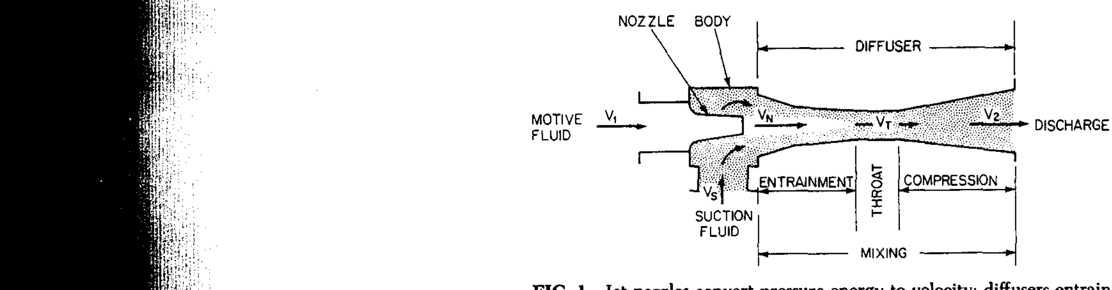


FIG. 1 Jet nozzles convert pressure energy to velocity; diffusers entrain and mix the fluids and convert velocity back to pressure.

where P_1 = static pressure upstream, $\mathrm{lb/ft^2}$ ($\mathrm{N/m^2}$)
P_s = static pressure at suction (nozzle tip), $\mathrm{lb/ft^2}$ ($\mathrm{N/m^2}$)
V_1 = velocity upstream of nozzle, ft/s (m/s)
V_N = velocity at nozzle orifice, ft/s (m/s)
γ_1 = specific weight (force) of motive fluid, $\mathrm{lb/ft^3}$ ($\mathrm{N/m^3}$)

Upstream of the nozzle, all the energy is considered static head, so that the velocity term V_1 drops out, yielding

$$\frac{V_N^2}{2g} = \frac{P_1 - P_s}{\gamma_1} \tag{2}$$

This term is called the *operating head.*

Across the diffuser, the same principle applies for the mixed fluid stream, except that the effect is the reverse of a nozzle; hence,

$$\frac{P_s}{\gamma_2} + \frac{V_T^2}{2g} = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g}$$

where P_s = static pressure at suction, $\mathrm{lb/ft^2}$ ($\mathrm{N/m^2}$)
P_2 = static pressure at discharge, $\mathrm{lb/ft^2}$ ($\mathrm{N/m^2}$)
V_T = velocity at diffuser throat, ft/s (m/s)
V_2 = velocity downstream, ft/s (m/s)
γ_2 = specific weight (force) of mixed fluids, $\mathrm{lb/ft^3}$ ($\mathrm{N/m^3}$)

At the discharge, it is assumed that all velocity head has been converted to static head; hence $V_2 = 0$ and

$$\frac{V_T^2}{2g} = \frac{P_2 - P_s}{\gamma_2} \tag{3}$$

This term is called the *discharge head.* The head ratio R_H is then defined as the ratio of the operating head to the discharge head:

$$R_H = \frac{V_N^2/2g}{V_T^2/2g} = \frac{V_N^2}{V_T^2} = \frac{(P_1 - P_s)/\gamma_1}{(P_2 - P_s)/\gamma_2} = \frac{(P_1 - P_s)\gamma_2}{(P_2 - P_s)\gamma_1} \tag{4}$$

Since ratios are involved, it is convenient to replace specific weight with specific gravity:

$$R_H = \frac{(P_1 - P_s)(\text{sp.gr.}_2)}{(P_2 - P_s)(\text{sp.gr.}_1)} \tag{5}$$

When the suction and motive fluids are the same, no gravity correction is required and Eq. 5 becomes

$$R_H = \frac{H_1 - H_s}{H_2 - H_s} \tag{6}$$

where $H_1 - H_s$ = operating head, ft (m)
$H_2 - H_s$ = discharge head, ft (m)

Entrainment conditions are defined by the basic momentum equation:

$$M_1 V_N + M_s V_s = (M_1 + M_s) V_T$$

where M_1 = mass of motive fluid, slugs (kg)
M_s = mass of suction fluid, slugs (kg)
V_N = velocity at nozzle discharge, ft/s (m/s)
V_s = velocity at suction inlet, ft/s (m/s)
V_T = velocity at diffuser throat, ft/s (m/s)

The velocity of approach at the suction inlet is zero; therefore rearranging yields

$$M_s = M_1\left(\frac{V_N}{V_T} - 1\right)$$

and the term below is defined as the *weight operating ratio:*

$$R_w = \frac{M_s}{M_1} = \frac{V_N}{V_T} - 1 \tag{7}$$

Observe that the term V_N^2/V_T^2 has previously been defined as the head ratio R_H; therefore

$$R_w = \sqrt{R_H} - 1 \tag{8}$$

The volume ratio R_q is then simply

$$\frac{Q_s}{Q_1} = R_w \frac{\text{sp.gr.}_1}{\text{sp.gr.}_2} \tag{9}$$

where Q_s = suction flow in volumetric units
Q_1 = motive flow in volumetric units

The maximum theoretical performance of eductors is calculated from the above relationships. In practice, there are energy losses associated with the mixing of two fluids and frictional losses in the diffuser. These losses are accounted for by the use of an empirical factor to reduce the theoretical maximum performance. Figure 2 shows this factor plotted against NPSH (net positive suction head) for a single-nozzle and annular-nozzle eductor. In an annular-nozzle eductor, the motive fluid is introduced around the periphery of the suction fluid, either by a ring of nozzles (Fig. 15) or by an annulus created between the inner wall of the diffuser and the outer wall of the suction nozzle (Fig. 14). The NPSH is the head available at the centerline of the eductor to move and accelerate suction fluid entering the eductor mixing chamber. NPSH is the total head in feet (meters) of fluid flowing and is defined as atmospheric pressure minus suction pressure minus vapor pressure of suction or motive fluid, whichever is higher.

The efficiency factor is introduced into Eq. 8 as

$$R_w = \epsilon \sqrt{R_H} - 1$$

This equation is used to calculate the motive quantity or pressure from the operating parameters. The nozzle and diffuser diameters are calculated from the equation $Q = wAV$, using suitable nozzle and diffuser entrance coefficients. The principal problems in design concern the size and proportions of the mixing chamber, the distance between nozzle and diffuser, and the length of the diffuser. Eductor designs are based on theory and empirical constants for length and shape. The most efficient units are developed from calculated designs which are then further modified by prototype testing.

Increased viscosity of motive or suction fluid increases the frictional and momentum losses and therefore reduces the efficiency factor of Fig. 2. Below 20 cP, the effect is minimal (approximately 5% lowering of ϵ). Above this value, the loss of performance is more noticeable and empirical data or pilot testing is used to determine sizing parameters.

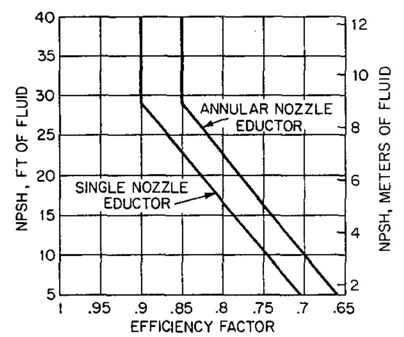


FIG. 2 NPSH versus efficiency factor. (Schutte and Koerting)

Figure 3 shows the operating ratio R_w versus the head ratio R_H for various lift conditions. The efficiency factor has been incorporated into this curve.

The final size of the eductor is determined by the discharge line and is based on normal pipeline velocities, which are usually 3 to 10 ft/s (0.9 to 3 m/s). Figure 4*a* and 4*b* are used for estimating eductor size. To illustrate the use of Figs. 3 and 4, consider the following example.

EXAMPLE 1 It is desired to remove 100 gpm (22.7 m³/h) of water at 100°F (38°C)

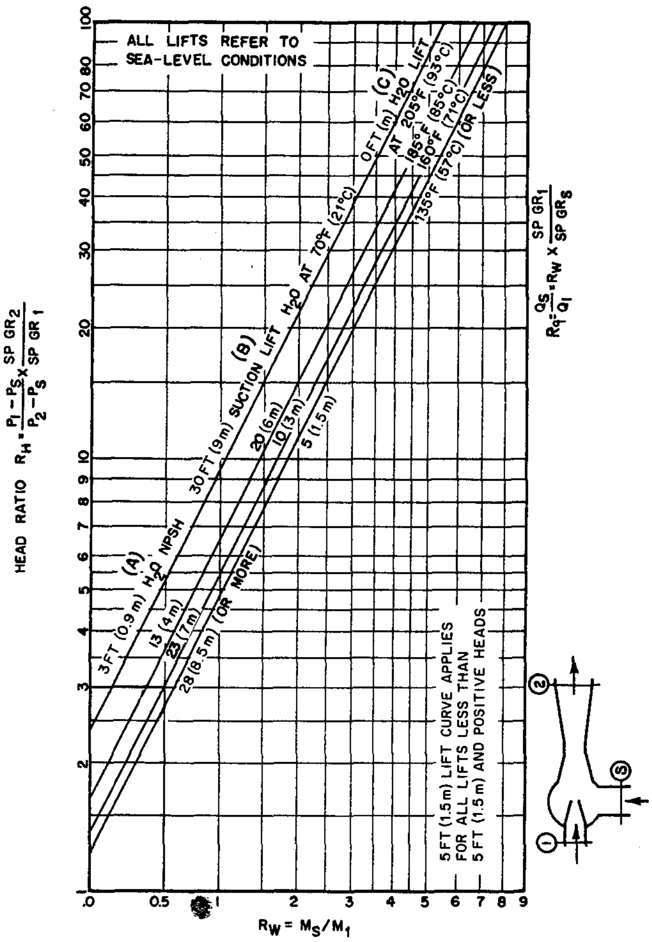


FIG. 3 Estimating operating ratios for liquid jet eductors. An eductor can be designed for only one head point. (Schutte and Koerting)

from a pit 20 ft (6.1 m) deep. Discharge pressure is 10 lb/in^2 (0.69 bar*) gage. Motive water is available at 60 lb/in^2 (4.1 bar) gage and 80°F (26.6°C). The eductor is to be located above the pit. Find the eductor size and motive water quantity required.

Solution To use Fig. 3, it is necessary to determine the NPSH and the head ratio R_H. The centerline of the eductor is chosen as the datum plane, and NPSH is taken to be atmospheric pressure minus suction lift minus vapor pressure at 100°F (38°C):

in USCS units $$NPSH = 34\text{ ft} - 20\text{ ft} - 1.933\text{ inHg}\left(\frac{13.6}{12}\right) = 11.81\text{ ft}$$

in SI units $$NPSH = 10.36\text{ m} - 6.1\text{ m} - 49\text{ mmHg}\left(\frac{13.6}{1000}\right) = 3.59\text{ m}$$

*1 bar = 10^5 Pa. For a discussion of bar, see *SI Units—A Commentary* in the front matter.

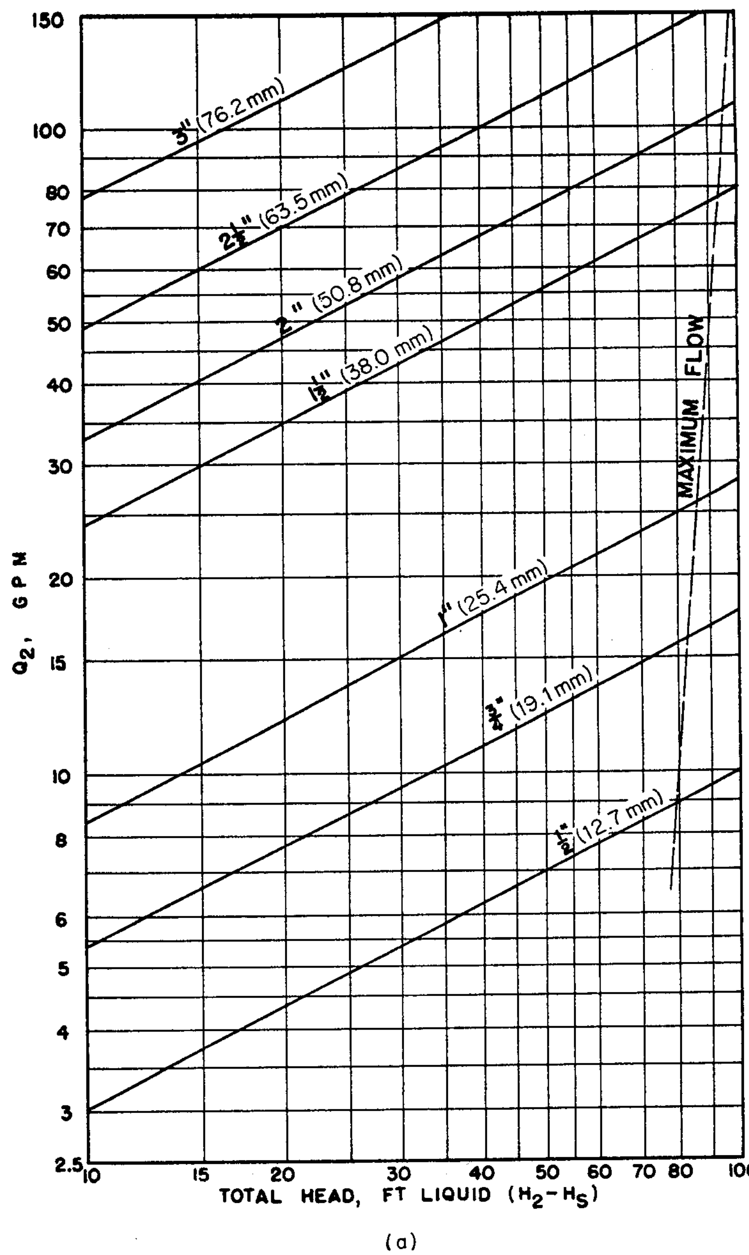
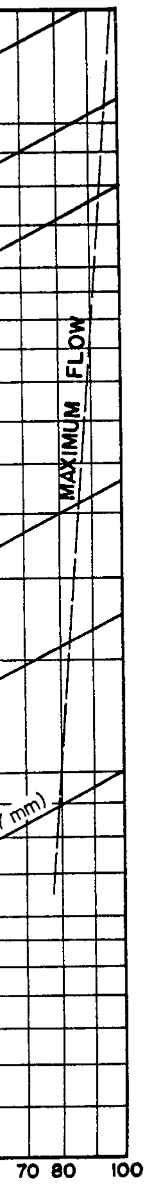
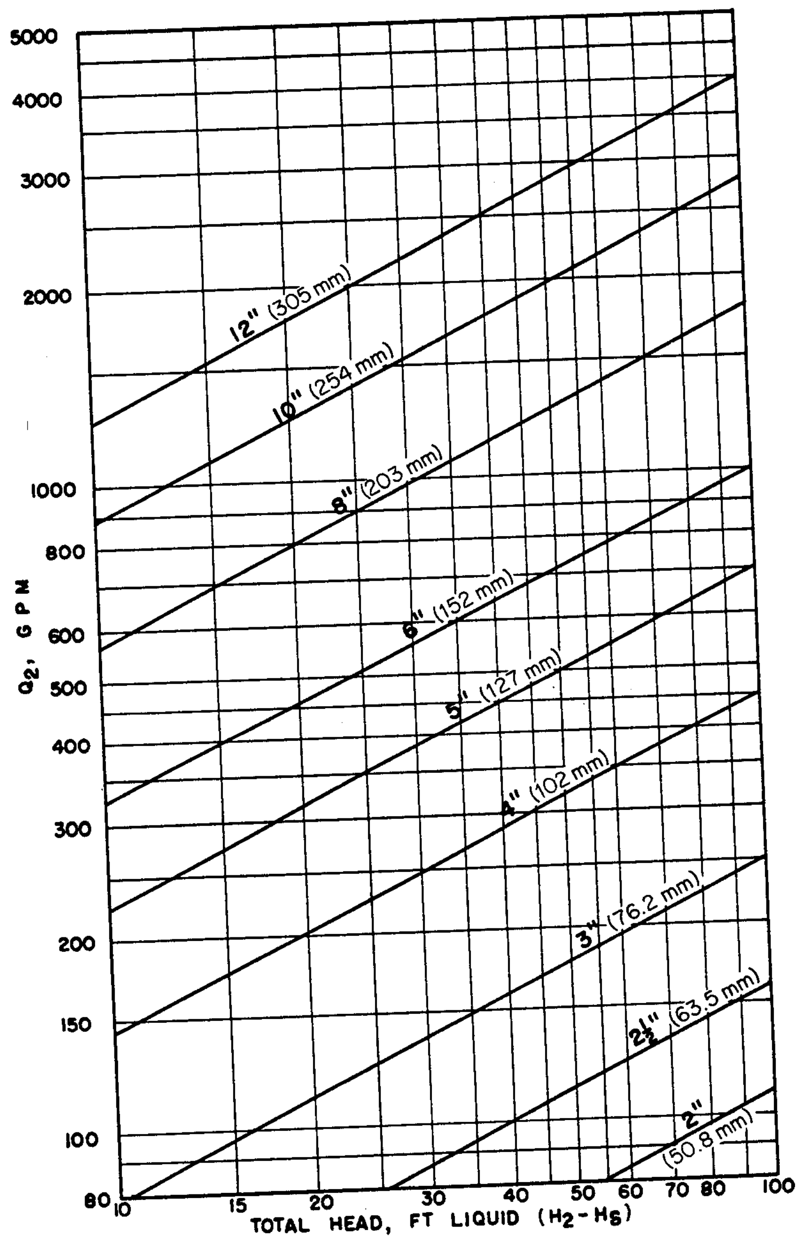


FIG. 4 Sizing curve (gpm × 0.227 = m^3/h; ft × 0.3048 = m).





(b)

FIG. 4 *(continued)*

Since motive and suction are the same fluid, it is convenient to work in feet (meters) rather than pounds per square inch (bar), and

$$P_1 = 60 \text{ lb/in}^2 \text{ gage} = 138.6 \text{ ft } H_2O \ (4.1 \text{ bar} = 42 \text{ m})$$

$$P_2 = 10 \text{ lb/in}^2 \text{ gage} = 23.1 \text{ ft } H_2O \ (0.69 \text{ bar} = 7 \text{ m})$$

$$P_3 = -20 \text{ ft } (-6.1 \text{ m})$$

Then

in USCS units $$R_H = \frac{138.6 - (-20)}{23.1 - (-20)} = \frac{158.6}{43.1} = 3.68$$

in SI units $$R_H = \frac{42 - (-6.1)}{7 - (-6.1)} = 3.68 \text{ m}$$

Enter Fig. 3 at $R_H = 3.68$ and $NPSH = 11.81$ (3.59 m); read $R_w = 0.48$. Since there is no gravity correction,

in USCS units $$R_w = R_q = \frac{0.48 \text{ gal suction}}{\text{gal motive}}$$

in SI units $$R_w = R_q = \frac{0.48 \text{ m}^3 \text{ suction}}{\text{m}^3 \text{ motive}}$$

The same result can be obtained by using the efficiency factor from Fig. 2. Then R_w is $0.77\sqrt{R_H} - 1 = 0.48$ and the required motive fluid is

in USCS units $$\frac{100 \text{ gpm suction}}{0.48} = 208 \text{ gpm at } 60 \text{ lb/in}^2 \text{ gage}$$

in SI units $$\frac{22.7 \text{ m}^3\text{/h}}{0.48} = 47.3 \text{ m}^3\text{/h at } 4.1 \text{ bar gage}$$

Discharge flow is

in USCS units $$208 + 100 = 308 \text{ gpm}$$

in SI units $$47.3 + 22.7 = 70.0 \text{ m}^3\text{/h}$$

The size is obtained from Fig. 4. Enter Fig. 4*b* at $Q_2 = 308$ gpm (70 m^3/h) and discharge head $(H_2 - H_3) = 23.1 - (-20) = 43.1$ ft [$7 - (-6.1) = 13.1$ m]; read eductor size of 4 in (102 mm) based on the discharge connection.

Note If there were any appreciable length of run on the discharge line, it would be necessary to calculate the pressure drop in this line and recalculate the eductor size after adding the line loss to the discharge head required. Frictional losses on the suction side must also be included. In the example chosen, however, 100 gpm (22.7 m^3/h) in a 4-in (102-mm) suction line 20 ft (6.1 m) long will have negligible frictional loss, less than 0.25 ft (0.08 m) H_2O.

Performance Characteristics Figure 5 illustrates the performance characteristics of eductors. Note the sharp break in capacity below the design point. For this reason all eductors are not designed for a peak efficiency. It is often advantageous to have a wide span of performance with lower efficiencies rather than a peak performance with very limited range.

Applications Beside the obvious advantages of being self-priming, having no moving parts, and requiring no lubrication, eductors can be made from any machinable material in addition to special materials, such as stoneware, Teflon,®* heat-resistant glass, and fiberglass. The applications throughout industry are too numerous to mention, but some of the more common will be discussed here. The type of eductor is determined by the service intended.

*Teflon is a registered trademark of E. I. DuPont de Nemours and Co., Inc.

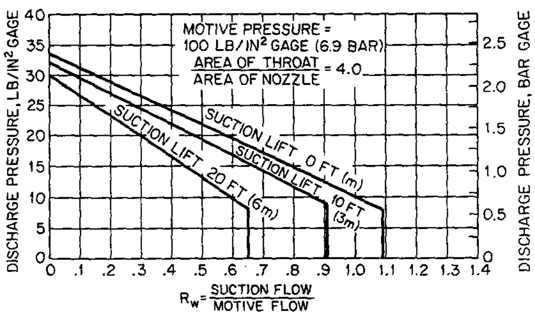


FIG. 5 Characteristic performance of an eductor.

GENERAL PURPOSE EDUCTORS Table 1 is a capacity table for a general purpose eductor used for pumping and blending. This type of eductor, illustrated in Fig. 6, has a broad performance span rather than a high peak efficiency point. Standard construction materials for this type of eductor are cast iron, bronze, stainless steel, and PVC. Typical uses include cesspool pumping, deep-well pumping, bilge pumping aboard ship, and condensate removal.

The following problem illustrates the use of Table 1.

EXAMPLE 2 Pump 30 gpm (6.81 m^3/h) of water from a sump 5 ft (0.61 m) below ground. Discharge to drain at atmospheric pressure. Motive water available is 40 lb/in^2 (2.8 bar) gage.

Solution Enter left side of Table 1 at 5 ft (1.5 m) suction lift and 0 lb/in^2 (bar) gage discharge pressure. Read horizontally across to 40 lb/in^2 (2.8 bar) gage operating water pressure. Read 9.6 gpm (2.18 m^3/h) suction and 7.3 gpm (1.66 m^3/h) operating fluid. These values are obtained in a 1-in (25.4-mm) eductor with a capacity ratio of 1.0.

To determine the capacity ratio of the required unit, divide the required suction by the quantity handled in 1-in (25.4-mm) eductor:

in USCS units $\quad \text{Capacity ratio} = \dfrac{30}{9.6} = 3.13$

in SI units $\quad \text{Capacity ratio} = \dfrac{6.81}{2.18} = 3.13$

Referring to the bottom of Table 1, a 2-in (50.8-mm) eductor with a capacity ratio of 4.0 is obtained. The required motive flow is then

in USCS units $\quad 4(7.3) = 29.2$ gpm

in SI units $\quad 4(1.66) = 6.64$ m^3/h

and the suction capacity is

in USCS units $\quad 4(9.6) = 38.4$ gpm

in SI units $\quad 4(2.18) = 8.72$ m^3/h

A 1½-in (38-mm) unit can handle 2.89 times the values in Table 1, or 27.7 gpm (6.3 m^3/h) suction when using 21 gpm (4.8m^3/h) motive water at 40 lb/in^2 (2.8 bar) gage. If suction flow rate is not critical, some capacity can be sacrificed in order to use a smaller and therefore lower-cost eductor. If optimum performance is desired, it is necessary to size a special eductor using Figs. 3 and 4.

Figure 7 illustrates more streamlined versions for higher suction lifts or applications involving the handling of slurries. This type of eductor is often used to remove condensate from vessels