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Duct Design for Effective Performance Design of Vacuum Nozzle

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ABSTRACT

The increasing importance of pipe services is obviously one of the inevitable consequences of industrial revolution. Added to this is the dire need to bring convenience to human life. Pipe has therefore become one of the most needed engineering materials in modern engineering designs. An approach to duct design is carefully examined. The nature of flow and pressure losses in ducts are important factors to consider in any duct design process. A design project on vacuum nozzle commonly used in the design of de-odorizing vessel in a typical vegetable Oil Refinery Plant is hereby considered. The design shows that a ¾ inch (19mm) pipe of 2.5mm thickness is required for a design vacuum pressure of 5mm Hg.

Keywords: *Duct Design, Design Pressure, Temperature, Vacuum Nozzle.*

1. INTRODUCTION

Ducts are generally used in transporting fluids under pressure. These include water, sewage, in-process foods, steam, oil, different kinds of gasses, and chemicals. The fluid in transit may sometimes undergo a change of phase inside the duct as the case of steam boilers. Generally, ducts are designed with great care to withstand internal pressure of the fluid and to meet with the prevailing operating conditions. With the available standard specifications for different sizes of pipes, design by selection best suits virtually all cases of pipe designs except in special and highly restricted cases where high cost of custom- made ducts may be overlooked. Mild steel pipes are generally in common use. The use of cast iron pipes is limited to pressures of about $0.7 N/mm^2$ because of the low resistance to shocks (Keith, 1982). Wrought iron and steel pipes are mainly used for conveying steam, gas, and oil. Pvc pipes are employed in domestic water supply networks, irrigation network systems, and in food and beverage industries. Brass pipes (in small sizes) find use in pressure lubrication systems. Pipes used in petroleum and gas industries are generally seamless, made of heat- resistant chrome molybdenum alloy steel. Such pipes can withstand pressures more than $4N/mm^2$ and temperatures greater than 400^oC.

In pipe networking, valves are normally installed at convenient points to ensure adequate flow control and so that sections can be isolated for easy repairs. Adequate clips positioned at appropriate intervals are necessary to prevent vibrations. Excessive pressure causes water hammer. Hence the design pressure of ducts is a major consideration. The longer the pipe length, the more the pressure drop. Also the more the number of fittings, the more the frictional losses.

2. FLOW IN A DUCT

A duct may be taken to represent any closed geometry with fluid flow inside. For most practical purposes the designer is mainly concerned with circular tubes or pipes for fluid flows. Square or rectangular ducts are sometimes employed for low pressure gas flows. It is therefore best to relate such designs of any shaped duct with the use of a geometric parameter called the Hydraulic Mean Diameter (Keith, 1982).

Fluid flow through ducts generally fall into two separate flow regimes, laminar or turbulent flow. For a Reynolds number (Re) below 2000 (based on the hydraulic mean diameter), the flow is usually laminar for all practical purposes, and turbulent when greater. At the entry to the duct the fluid flow velocity is ideally uniform and equal to the mean velocity of the flow, U_m. As the fluid flows along the duct the effect of fluid viscosity tends to slow down the flow near the duct wall. However, to maintain continuity even as the flow slows down near the wall, the remainder of the flow near the center of the duct must have to accelerate above the inlet velocity. The flow thus develops a boundary layer at the wall which increases in thickness as the fluid flows along the duct until at a certain position when the boundary layer extends across the duct to meet that of the opposite wall, Fig.1.0.

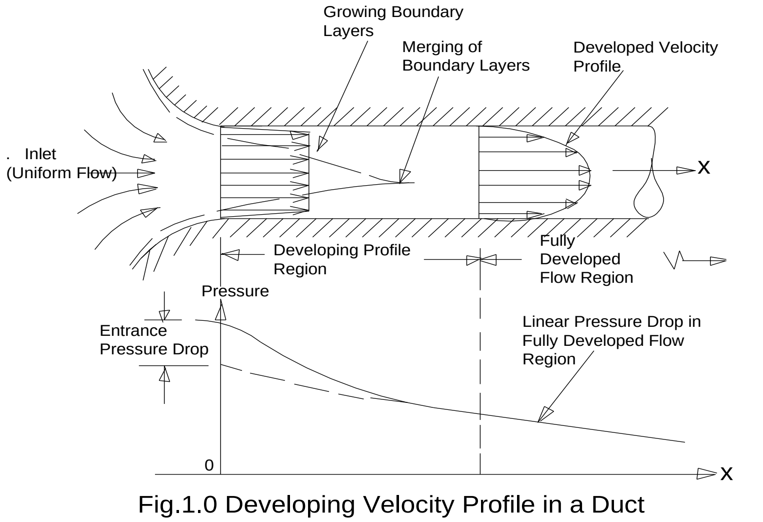

Fig.1.0 Developing Velocity Profile in a Duct

When the boundary layer extends across- sectional area of the duct, the flow is said to be fully developed. If there is no unevenness in the duct and the flow is symmetrical about the center line, the velocity profile becomes parabolic. From the entry of the duct to the point where the flow is fully developed, the duct length is found to be approximately $0.029R_e$ diameters (Knudsen, J.G.et al, 1958). For instance, if the flow is laminar with a Reynolds number of 2000, then the length to diameter ratio for a fully developed flow is given by

$$l/d = 0.029R_e = 58$$

This means that a length of about sixty diameters is required under the stipulated flow conditions for a fully developed flow. Above the Reynolds number of 2000, flow in long straight ducts becomes turbulent and unsteady, causing a random motion in the flow. This can be illustrated by injecting dye into the water flow. With laminar flow, a filament of dye will remain distinguishable, whereas with turbulent flow the dye filament quickly loses its form as the dye disperses in the unsteady water flow. At the entrance of a duct with turbulent flow, the velocity profile is again ideally uniform. As the fluid moves along the duct, a laminar boundary layer begins to build up, but this quickly changes to a turbulent boundary layer.

3. DUCT DESIGN

This involves the determination of various parameters such as the inside diameter of duct, wall thickness, design pressure, as well as the design temperature.

a. Duct Diameter

The hydraulic mean diameter is defined as;

d_m = (4 X duct cross- sectional area) / wetted perimeter of duct

In the case of a circular pipe, d_m equals the pipe diameter, d since the cross- sectional area is $\pi d^2/4$ and wetted perimeter πd. thus for a circular pipe;

$$d_m = (4X\pi d^2/4) / \pi d = d \quad \text{--------------------------- (1)}$$

Accurate design of inside diameter of duct will depend on;

1. The flow velocity of the fluid, V
2. The quantity of fluid flowing per minute, Q
3.

$$Q = \text{Area x velocity} = (\pi d^2/4) \text{ x } V \quad \text{---------------------- (2)}$$

Where $d = [4/\pi \text{ x } Q/V]$

b. The Wall Thickness

Pipes for conveying high pressure fluids are necessarily made thicker to withstand the high pressure force. Pressure is therefore a major determinant of the duct wall thickness (www. Pipeline 101).

Duct wall thickness is given by (perry, R.H, 1998),

$$t = [(PD/2\sigma + p) + C][100/100\text{-}a] \text{ in mm} \quad \text{--------------------- (3)}$$

Where

p = design pressure, N/mm^2 ; D = outside diameter of duct, mm

σ = maximum permissible design stress, N/mm^2;

a = percentage negative manufacturing tolerance on thickness, C = corrosion allowance.

Where straight pipes are to be used for a pipe bend, the minimum thickness, t_b is given as,

$$t_b = \{(PD/2\sigma+P) + b + C) \text{ x } (100/100 - a)\} \text{ in mm} \quad \text{----------- (4)}$$

Where b = 1 / 2.5 x D/R (PD/2σ + p) in mm. generally, R ≥ 3D

c. The Design pressure

This is the maximum permissible working pressure with which the design specifications are made. It should not be less than the highest set pressure of the safety or relief valve. Stresses in pipes are caused mainly by the internal fluid pressure. This can be determined by using Lame's equation (www.pigs). The tangential stress at any point x is given by,

$\sigma t = \{ P(r_{.i})^2 / r_o^2 - r_o^2)\{ 1 + r_o^2/x^2\}$ ---------- (5)

and the radial stress at a given radius, x is;

$\sigma_r = \{ P(r_i^2) / r_o^2 - r_i^2\} \{I - r_o^2/x^2\}$ -----------(6)

Where P = internal fluid pressure in the duct

r_i = Internal radius of the duct ; r_o = Outer radius of dust

The tangential stress is usually maximum at the inner surface (when x = r_i) of the pipe and minimum at the outer surface (when x = r_o) of the pipe. Hence, substituting the values of x = r_i and x = r_o respectively in equations (5) and (6) above; maximum tangential stress at inner surface of duct,

$\sigma_{t(max)} = P (r_o^2 + r_i^2) /_o^2 - r_i^2$ --------------- (7)

Also the minimum tangential stress at the outer surface is,

$\sigma_{t(min)} = 2P (r_i^2) / r_o^2 - r_i^2$ ------------- (8)

The allowable stress, $\sigma_{t'}$ is usually less than six times the pressure, P inside the duct. That is; $\sigma_t < 6P$

From lame's question, duct wall thickness is therefore given by,

$t = [(\sigma_t + P)/ (\sigma_t - P)]^{1/2} - 1$ ---------------- (9)

d. The Design Temperature

This is the maximum temperature which the internal fluid can attain. For pipes used for superheated steam, the design temperature is equal to the operating steam temperature for the pipeline provided the temperature at the super-heater outlet is controlled (www.duke).

4. DESIGN OF VACUUM NOZZLES

The philosophy is for an economic sizing of pipes for the required flow conditions. In general, the upper bounds for pressure drops is set at 3448 N/m^2 per 100 ft (about 30.48m) for gas and vapour lines, and 68950 N/m^2 per 30.48m for liquid lines (Backhurst, et al, 1983); (www.co.ba md).

For commercial steel or wrought iron, the pressure drop is given by,

$\Delta P = m W^2 / p d^n$ --------------- (10)

Where, W = fluid flow rate, Ib / hr ; P = density of fluid, Ib / ft^3

d = internal diameter of pipe, inches ΔP = pressure drop, Psi / 100 ft ; and m = 6.86 x 10^{-6} ; n = 5.1815

Allowable pressure drops are generally set at 10 Psi or 58950 N/m^2 for process heat exchangers. And 25 Psi (172,375 N/m^2) for control valves of equivalent length.

a. PROJECT: Design of vacuum Nozzle for De-odorizing Vessel in a Vegetable Oil Refinery plant

Design Data:

Operating temperature ---- 180^{0}C
Diameter of deodorizing vessel ---- 1.86m
Height of deodorizing vessel ---- 3.72m
Duration of vacuum operation =20mins

The density of moist air is given by (Andersen 1978);

$\rho_{air} = [1.2929 (273.13/T) (B-0.3783 e)] /760$

where T = absolute temperature = operating temperature = 180^0 C + 23=273 = 453 K

B = barometric pressure, mm Hg= atmospheric pressure – vacuum pressure (or design pressure) =759.7 mm Hg

e = vapour pressure of moisture in the air = vapour pressure of palmitic acid at the operating temperature of 180^0 = 2.4mm Hg

p_{air} = 1.2929 (273.13 / 453) [(754.7-0.3783 x 2.4) / 760)] = 0.773kg/m^3

Volume of Deodorizer vessel

= π D^2 L / 4

Where, D = diameter of vessel, L =height

Volume, V = π (1.86)^2 x 3.72 / 4 = 10.10 m^3

Considering half-full the volume of vessel, ½ V = 1 / 2 x 10.10 = 5.05 m^3

Mass of air, m = p_{air} V= 0.773 x 5.05 = 3.90kg of air

For 20 minutes vacuum operation;

Air flow rate, W = 3.90 / 20 x 60 = 0.00325 kg / s

From Eqn.(10), $d^n = m W^2 / p Ap$

Where, w = 0.00325 kg/s = 0.00717 Ib/s = 25.80 Ib/h

$p = p_{air}$ = 0.773 kg/m^3 = 0.0483 Ib/ft^3

$d^n = (6.86 \times 10^{-6} \times 25.8^2) / (0.0483 \times 0.5) = 0.189$

$d = (0.189)^{1/n} = (0.189)^{-1/5.1815} = 0.725$ inch = 18.4mm

Use ¾ inch pipe (19.0 mm Dia. Pipe)

Using equation (3), duct thickness,

$t = [(PD/ 2\sigma + p) + C] [100 / (100 - a)]$ in mm

where, p = 5 mm Hg = 6.67 x 10^{-8} n /mm^2 ; D = 19.0 mm ;

$\sigma = 3448$ N/m ^{2} = 3.448 x 10 $^{-3}$ N/ m; C = 2.0 ; and a = 20 %

t = [{6.67 x 10 $^{-8}$ x 19) / (2 x3.448 x 10 – 3 + 6.67 x 10 $^{-8}$)} + 2.0] x [100 / (100 – 20)] = 2.5 mm

5. CONCLUSION

Duct design obviously involves careful determination of all relevant parameters. Any mistake is likely to give a misleading result. Usually the nearest standard duct size is chosen. For instance, a ¾ inch pipe is chosen for the design value of 0.725 inch. Observe that in using equation (10) all the parameters were computed in accordance with their respective units upon which the constants m and n were established. The final value of duct diameter is then converted to SI unit. With the computed value of 2.5 mm for the pipe thickness, a 3mm thick pipe is recommended for the suction side of the vacuum pump.

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