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Optimal Cross-Sectional Shape of Gas/Air Ducts

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Abstract

In industrial plants, ships, and buildings, a large amount of gas and air ducts are applied for equipment connection, HVAC, medium transport, and exhaust, etc. These ducts can be designed in varied cross-sectional shapes, such as round or rectangle. The author reveals through geometric calculation of the duct cross-sectional shapes and engineering experiences that the round cross-section is an optimal shape in the duct system. The round duct has the shorter perimeter than the other cross-sectional shape ducts and the stronger structure in the same working condition. The material saving of the round duct due to the shorter perimeter is quantitatively determined. In the pater, it is shown that the round duct is economically attractive. The economic analysis for the material cost saving is illustrated by an example. For a long duct system, the material and material cost savings are significant. It is suggested that the round duct in the gas and air duct system should have priority as long as the field conditions are allowed. In the paper, the material cost saving is also converted to PW, AW, and FW used for LCC economic analysis.

Keywords

Optimal, Ducts, Cross-Sectional Shape, Economic and Cost Analysis

1. Introduction

Gas and air duct systems are widely applied in industrial plants, ships, and buildings for the purposes of equipment connection and medium transport, such as in HVAC and exhaust systems. The cross-sectional shapes of the ducts are frequently designed and built in rectangle, square, or round. The duct material most commonly is galvanized metal sheet. Insulations are used which depend on the duct application purposes. From a geometric view, the round duct has the least perimeter compared to the rectangular and square ducts with the equal flow sectional area. Therefore, the material of the round duct comparing to the square or rectangle duct with the equal flow sectional area can be reduced. While with the equal perimeters, the round duct has the greatest flow sectional area, which will reduce the flow friction apparently. Nevertheless, the round duct should be an optimal design in the ductwork application. The perimeter and cross-sectional area relations of these ducts are shown in **Table 1**. If a duct system has thousands feet long, the material saving and material cost saving will be significant and other benefits can be obtained by using the round duct.

2. Material Saving and Benefits Using Round Duct

In ductwork system design, the duct cross-sectional shape can be either round or rectangle with the same flow friction which means the equal flow sectional area. The equation relating diameter D of the round duct and side lengths of the rectangular duct will be [1]

$$D = \frac{1.3a(b/a)^{\frac{5}{8}}}{(1+b/a)^{\frac{1}{4}}} \tag{1}$$

After a few manipulations, Equation (1) can be expressed as

$$D = \frac{1.3(ab)^{\frac{5}{8}}}{(a+b)^{\frac{1}{4}}} \tag{2}$$

Then k, a perimeter ratio of the round duct to the rectangular duct, is

$$k = \frac{\pi D}{2(a+b)} = \frac{1.3\pi(ab)^{\frac{5}{8}}}{2(a+b)(a+b)^{\frac{1}{4}}} \tag{3}$$

Equation (3) becomes after rearrangement

$$k = 0.65\pi \sqrt[8]{\frac{R^5}{(1+R)^{10}}} \tag{4}$$

where $R = a/b =$ long-side length/short-side length

From the manufacturing consideration, R shall be kept below 8. The results of perimeter ratio k varies with aspect ratio R and description are listed in **Table 2**.

It can be seen that less perimeter needs for the round duct comparing to the rectangular duct. The larger R is, the less k has, which means less material for the round duct than that for the rectangular duct. From the practice of industry, R value usually is

Table 1. Perimeter and area relations.

	Shape	Equal Perimeters	Equal Areas
Rectangle		Has the least area	Has the greatest perimeter
Square		Has a greater area than rectangle	Has a perimeter less than rectangle
Round		Has the greatest area	Has the least perimeter

Table 2. Variance of *K* with *R.*

R Value	*k* Value	Perimeter of a round duct is
1	0.86	85% a rectangular duct
2	0.80	80% a rectangular duct
3	0.72	72% a rectangular duct
4	0.65	65% a rectangular duct
5	0.60	60% a rectangular duct
6	0.55	55% a rectangular duct
7	0.51	51% a rectangular duct
8	0.48	48% a rectangular duct

kept around 2. The duct material, therefore, can be save 20% by using the round duct. In other words, the material cost saving is 20% for the round duct comparing to the rectangular duct.

1) Metal Sheet Material Cost Saving

Galvanized metal steel is the most common material used in ductwork fabrication. Cost for fabricating ductworks is usually based on the total mass of the duct and fittings. For a straight duct with galvanized metal steel, the unit price of gauge 26, 24, 22, 20, and 18 less than 454 kg (1000 pounds) is about $5.79/kg ($2.63/lb) [2]. **Table 3** shows the material cost saving per unit length for an813mm x 406mm (32" × 16") duct with $R = 2$.

2) Stress and Structure Consideration

- Stress Concentration

As we know, a geometric stress concentration will occur whenever there is a discontinuity or non-uniformity on the surface of an object. The perimeter of a rectangular duct has sharp turns while the perimeter of a round duct continues smoothly. The round duct with less stress concentration, therefore, will have a longer life time in operation.

- Structure Stability

It is also known when a pressurized air or gas stream is flowing in the ductwork, the duct will stand for internal force. The round duct has the stronger structure stability than the rectangular duct as per the internal stress analysis. Therefore, strength components used in the rectangular duct may not be necessary in the round duct, such as anger-steels in section side and flow direction. It will reduce the duct material and labor in fabrication. As a result, the material and fabrication cost is reduced.

3) Other Savings

- If insulation needed, the ducts are typically lined with faced fiber glass blankets (duct liner) or wrapped externally with 25 mm by 50 mm (1" by 2") layer fiber glass blankets (duct wrap). Since the perimeter of the round duct is less than that of the rectangular duct, the insulation materials will be reduced.

Table 3. Material cost savings per unit length.

Gauge	Thickness mm (inch)	Mass kg/m^2 (lbs/ft^2)	Cost Savings \$/m (\$/ft)
26	0.56 (0.022)	4.423 (0.906)	12.50 (3.81)
24	0.71 (0.028)	5.644 (1.156)	15.98 (4.87)
22	0.86 (0.034)	6.864 (1.406)	19.42 (5.92)
20	1.02 (0.040)	8.085 (1.656)	22.87 (6.97)
18	1.32 (0.052)	10.526 (2.156)	29.76 (9.07)

- Delivery cost is based on the material mass, which is about \$0.33/kg (\$0.15/lb) [2] typically. Since duct mass is dropped due tothe duct material reduction, the delivery cost will be reduced consequently.

Example:

A 305 m (1000 ft) long ductsystem will supply 102 m^3/minute (3600 CFM) air. In design, the friction of per 305 m (100 ft) duct is 2 mm (0.08") W.C., and a diameter D = 610 mm (24") round duct is selected [3]. With the equal friction, an 813 mm × 406 mm (32" × 16") rectangular duct can be used alternatively. Therefore,

The perimeter of the round duct is

L = πD = 1.92 m (6.3 ft)

The perimeter of the rectangular duct will be

L = 813 mm × 406 mm (32" × 16") = 2.4 m (8.0 ft)

For the 305 m (1000 ft) long 22 gauge duct system, the total duct material saving will be

Material saving per unit square area = 305 m × (2.4 m − 1.92 m) = 146.4 m^2 (1576 ft^2)

Referring to **Table 3**, the total material cost saving for gauge 22 will be

Material cost saving = 305 m × 19.42 \$/m =5923 \$

Table 4 shows the material cost savings for a 305 m (1000 ft) long duct system with gauge 26, 24, 22, 20, and 18 in the same design conditions, respectively. It can be seen for a long duct system, the material cost saving is significant!

3. Material Cost Saving in LCC Analysis

The material cost saving can be applied with other saving in life cycle cost (LCC) analysis to have the total cost savings of a duct system during the assigned system lift time. The other savings, for example, O & M cost and salvage or MV cost. The material cost saving need to be converted to PW, AW, and FW in the LCC analysis [4]. The PW, AW and FW of material cost saving are calculated by

$$\text{PW} = \text{Material Cost Saving}(\text{S}) \tag{5}$$

$$\text{AW} = \text{Material Cost Saving}(\$)(A/\text{P}, i\%, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

$$\text{FW} = \text{Material Cost Saving}(\$)(F/\text{P}, i\%, n) = (1+i)^n \tag{7}$$

As an illustration, the PW, AW, and FW of the material cost saving of gauge 22 from the above example in Section 2 with the following assignments are shown in **Table 5**.

Table 4. Material cost savings.

Gauge	Saving per Unit Length $/m ($/ft)	Material Cost Saving $
26	12.50 (3.81)	3810
24	15.98 (4.87)	4870
22	19.42 (5.92)	5920
20	22.87 (6.97)	6970
18	29.76 (9.07)	9070

Table 5. Savings with variation of *i* and *n*.

n	PW [$]	AWb [$]			FW [$]		
		6%	8%	10%	6%	8%	10%
15	5920	610	691	779	14,188	18,779	24,699
20	5920	516	603	696	18,986	27,593	39,827
25	5920	463	555	652	25,408	40,543	64,141
30	5920	430	526	628	34,002	59,571	103,300

Interest Rate (i) = 6%, 8%, and 10%, respectively

Life Time (n) = 15, 20, 25, and 30 years, respectively

4. Conclusion

The cross-sectional shape of a gas and air duct system applied for equipment connection, HVAC, medium transport, and exhaust can be selected in either round or rectangle. From geometric calculation and stress analysis, however, the round duct has the less perimeter and stronger structure of the flow. As a result, the duct material can be saved with the equal flow friction and other benefits, such as the ductwork life time can be obtained in the same working condition by using the round duct comparing to the rectangular duct. The calculation from the example illustrates for a large duct system, the material and material cost saving are significant.

- It is concluded that the round cross-section shape is optimal comparing to the square shape and rectangle shape for the gas and air duct system.
- It is suggested the round duct in the gas and air ductwork should be applied as long as the field conditions are allowed.

References

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Abbreviations

AW: annual worth
CFM: cubic feet per minute
D: round duct diameter
FW: future worth
HVAC: heating, ventilation, and air conditioning
L: perimeter of duct cross-section
LCC: life cycle cost
MV: market value
PW: present worth
R: aspect ratio
a: short-side length of rectangular duct
b: long-side length of rectangular duct
ft: foot, feet
i:annual interest rate
*k:*perimeter ratio
lb: pound
n: life time period
$: US dollar

Conversions

	U.S. Customary	SI
Length	1 inch	25.4 mm
	1 foot	0.3048 m
Mass	1 pound	4.5359 kg