

## A CASE FOR INTRODUCING THERMAL-DESIGN OPTIMISATION USING EXCEL SPREADSHEET

El-Awad M.M.\* and Abuharaz M.  
 \*Author for correspondence  
 Mechanical Engineering Department,  
 Faculty of Engineering, University of Khartoum  
 P.O. Box 321 Khartoum, Sudan,  
 E-mail: mmelawad09@gmail.com

### ABSTRACT

Thermal-design optimisation is an iterative process which involves the evaluation of many thermo-physical properties that vary with temperature and/or pressure. Therefore, suitable modelling software, such as Engineering Equation Solver (EES) or Mathcad, is usually used. However, such proprietary applications may not be available to many educational institutions in developing countries. This paper presents a case for introducing thermal-design optimisation to engineering students by using Microsoft's Excel as a modelling platform. The design case demonstrates how the principles of thermo-fluids and economics can be applied so as to find the optimum diameter for an air-conditioning duct. The paper describes the solution steps and provides all the equations needed to solve the case with Microsoft Excel. The paper also highlights the importance of using VBA (Visual Basic for Applications) for developing user-defined functions when repetitive or complex calculations are met. VBA is used to develop a general-purpose function that can be used by Excel users for linear interpolation of tabulated data that depend on a single variable.

### INTRODUCTION

By producing or consuming mechanical or electrical work and by releasing heat and/or hot or cold streams and reactive exhausts, thermal systems experience significant energy and mass interactions with their surroundings. The large-scale energy uses in thermal systems has resulted in severe economic and environmental impacts. Therefore, increasing attention is being given to developing efficient, yet economical, designs of these systems. Mechanical engineering curricula now introduce the design of thermal systems as a compulsory course for senior students. Compared to traditional mechanical design, thermal design is more associated with principles of thermo-fluids (thermodynamics, fluid mechanics, and heat transfer). In a good thermal-design case, the principles of these three subjects would be applied, together with engineering economics, so as to reach an optimum design. However, the search for an

optimum design is an iterative process that involves the determination of many thermo-physical properties. Therefore, solving a thermal-design problem by using property tables or charts is both tedious and inaccurate; which makes the use computer-based methods mandatory.

### NOMENCLATURE

$A$	[m <sup>2</sup> ]	Area
$c$	[\$]	Cost per duct unit
$c_p$	[J/kgK]	Specific heat at constant pressure
$c_v$	[J/kgK]	Specific heat at constant volume
$D$	[m]	Duct diameter
$h$	[J/kg]	Specific enthalpy
$h$	[W/m <sup>2</sup> K]	Heat-transfer coefficient
$h_f$	[m]	Friction head loss in duct
$k$	[W/mK]	Thermal conductivity
$k_s$	[m]	Roughness height of duct material
$L$	[m]	Duct length
$\dot{m}$	[kg/s]	Mass flow rate of air
$Nu$	[-]	Nusselt number
$P$	[Pa]	Pressure
$Pr$	[-]	Prandtl number
$Q$	[m <sup>3</sup> /s]	Air flow rate
$\dot{Q}$	[W]	Rate of heat transfer
$R$	[J/kgK]	The gas constant
$Re$	[-]	Reynolds number
$T$	[K]	Temperature
$\bar{U}$	[W/m <sup>2</sup> K]	Overall heat-transfer coefficient
$V$	[m/s]	Air velocity
$\dot{W}$	[W]	Rate of work transfer
Special characters		
$\rho$	[m <sup>3</sup> /kg]	Air density
$\mu$	[kg/ms]	Dynamic viscosity
$\omega$	[kg/kg]	Absolute humidity
$\phi$	[-]	Relative humidity
Subscripts		
$s$		Surface
$sat$		Saturation pressure or temperature
$\infty$		Ambient condition

Thermal-design projects are usually carried out with the help of a computer software, such as ASPENPLUS, PROCESS, and CHEMCAD[1]. These applications have the capability to determine the thermal properties of the fluids involved at various temperatures and/or pressure. Standard textbooks in thermal engineering also use general-purpose software such as Engineering Equation Solver (EES) or Mathcad to deal with design problems and calculation-intensive illustrations. REFPROP, which is a software dedicated to the evaluation of fluid thermal properties which is developed by NIST [2], can be annexed to various modelling platforms such as FORTRAN, Matlab, and Excel. Unfortunately, engineering students in many developing countries do not have access to most of these applications which are protected by proprietary rights. The software shortage, which is more restrictive than the shortage in computers themselves, further hinders the graduate engineers from playing their important role in national and industrial research and development activities.

Microsoft's Excel is a popular application that is free from the restrictions of proprietary software. Although simple to learn and easy to use, Excel has many built-in functions and iterative tools that give it the ability to solve a wide range of engineering problems. Moreover, the capabilities of Excel as a modelling platform for thermal design can be extended significantly by taking advantage of Visual Basic for Applications (VBA). VBA can be used to develop special user-defined functions (UDFs) for determining fluids thermal properties from relevant equations. Since both Excel and VBA are packaged with every newly-bought personal computer or laptop, they form an affordable computational platform for engineers and engineering colleges particularly in developing countries.

A number of previous publications dealt with the use of spreadsheets in engineering education [3,4]. The present paper uses Excel as modelling platform to present a simple thermal-design case that demonstrates how the principles of thermofluids and economics can be jointly applied so as to find an optimum solution to a thermal-design problem. The paper also highlights the advantages of using VBA for developing user-defined function; which make the Excel-VBA combination a powerful modelling platform for thermal-design optimisation.

The present design case has been introduced within an advanced thermal systems (ATS) course taken by senior mechanical engineering students. Prior to this 3-credit-hour course, the students took one 4-credit-hour course on thermodynamics, one three-credit-hour course on fluid-mechanics, and one 4-credit-hour course on heat-transfer. The 3 credit hours of the ATS course include 2 credit hours for engineering science and 1 credit hour for engineering design. Thus, the course is not a design-based module but a design project is a major part of it.

## THE THERMAL DESIGN CASE

The thermal-design case presented here relates to an air-conditioning system for hot and humid air. The system, which involves a cooling-and-dehumidification process followed by a heating process, was described by Suryanarayana and Arici [5] who determined the cooling and heating loads from a thermodynamic analysis. The present design case extends the analysis so as to determine the optimum diameter for the air-conditioning duct based on total owning cost. The principles of fluid-dynamics are applied to estimate the frictional pressure loss and power of the fan. Heat-transfer principles are applied to determine the rate of heat-transfer from the surroundings and the additional heating load that must be supplied by the heating system. The optimum diameter of the duct is then determined by minimizing the total annual owning cost, which is the summation of investment and energy costs.

Figure 1 shows the air-conditioning system that takes in air at an ambient condition of  $10^5\text{Pa}$ ,  $40^\circ\text{C}$  and 70% relative humidity and delivers the conditioned air at  $10^5\text{Pa}$ ,  $20^\circ\text{C}$  and 50% relative humidity. The conditioned air is to be transported horizontally from the air-conditioner through the attic of a warehouse to the required area which is 25 m away. In order to save part of the energy needed for heating the chilled air after the cooling-and-dehumidification process, the duct is left un-insulated so as to allow for convection heat transfer from the surrounding air. The average temperature of air at the outer surface of the duct is  $30^\circ\text{C}$  and natural circulation provides a convection coefficient of  $3\text{ W/m}^2\cdot\text{K}$ .

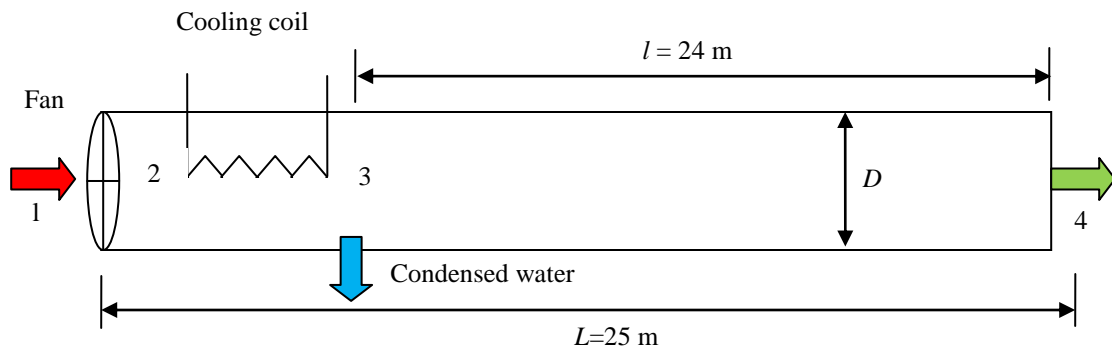


Figure 1. The thermal-design case.

Table 1: Initial cost of the air-conditioning duct unit [6]

D (inch)	≈ D (m)	Gauge	Cost per 0.9-m unit (\$)	D (inch)	≈ D (m)	Gauge	Cost per 0.9-m unit (\$)
4	0.10	26	8.99	12	0.30	26	22.49
5	0.13	26	10.49	14	0.35	24	30.99
6	0.15	26	11.49	16	0.40	24	33.99
7	0.18	26	12.99	18	0.46	24	39.99
8	0.20	26	14.49	20	0.50	24	49.99
9	0.23	26	15.99	22	0.55	24	55.99
10	0.25	26	16.99	24	0.60	24	79.99

It is required to determine the duct's diameter that minimizes the total annual cost based on the following information:

1. Hours of operation per day = 4 – 16 hours
2. Cost of electricity = 0.1 – 0.2 US dollar (\$) per kWh
3. The air duct is to be assembled from prefabricated cylindrical units made of galvanized sheet metal the cost of which is as shown in Table 1 [6]
4. Lifetime = 15 years.

#### SOLUTION PROCEDURE AND ANALYTICAL MODEL

The solution procedure follows the following main steps:

1. Fluid-flow calculations to determine the duct's friction losses and fan power.
2. Psychrometric calculations to determine the cooling and heating loads
3. Heat-transfer calculations to determine the rate of convection heat-transfer along the duct from surrounding air and, therefore, the required additional heating load.
4. Cost calculations to determine the total cost, which is the summation of the annual initial and energy costs.

Each step requires a set of equations that form a submodel in the overall analytical model. The optimum duct diameter is obtained by comparing the total costs at various diameters and selecting the diameter that gives the minimum total cost.

#### Fluid-flow submodel to determine the fan power

The fluid-flow problem is to determine the duct's head loss and fan power at a selected duct-diameter. The solution procedure goes as follows:

- a. Select a diameter ( $D$ ).
- b. Calculate the air velocity ( $V$ ) and Reynolds number (Re) from:

$$V = Q/A \quad (1)$$

$$Re = \frac{\rho VD}{\mu} \quad (2)$$

Where  $Q$  is the volume flow rate of air,  $A$  the cross-sectional area of the duct ( $A = \pi D^2 / 4$ ), and  $\rho$  and  $\mu$  are the air density and dynamic viscosity, respectively.

- c. Calculate the head-loss from the Darcy-Weisbach equation [7]:

$$h_f = f \left( \frac{L}{D} \right) \frac{V^2}{2g} \quad (3)$$

Where,  $L$  is the duct's length and  $f$  is the friction factor which is obtained from [7]:

$$f = 0.25 / \left[ \log_{10} \left( \frac{k_s}{3.7D} + \frac{5.74}{Re^{0.9}} \right) \right]^2 \quad (4)$$

- d. Calculate the fan power ( $\dot{W}_{fan}$ ) from the power equation:

$$\dot{W}_{fan} = \rho g Q h_f \quad (5)$$

#### Psychrometric submodel to determine the cooling and heating loads

Figure 2 shows the air-conditioning process on a psychrometric chart. The figure shows that the slightly compressed air after the fan at point 2 is chilled by the refrigeration system until its temperature is reduced to  $T_3$  so that part of the airborne water-vapour is condensed. Simple heating brings the air to the required condition at point 4. In order to calculate the required cooling and heating loads, the conditions at point 2 and point 3 have to be determined. The pressure at point 2 is obtained by adding the fan's pressure head to the pressure at point 1 and the temperature is obtained by assuming an isentropic compression process in the fan:

$$P_2 = P_1 + \rho g h_f \quad (6)$$

$$T_2 = T_1 \times \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \quad (7)$$

Where  $k$  is the ratio of specific heat for air ( $k = c_p/c_v$ ).

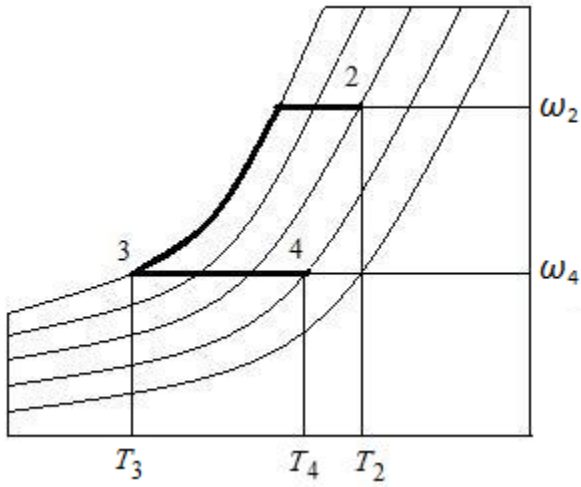


Figure 2. The air-conditioning process

The condition at point 3 is determined from the fact that at point 3, the relative humidity ( $\phi$ ) equals 100% and the specific humidity ( $\omega$ ) equals that at point 4. Specific humidity ( $\omega_4$ ) is calculated from [9]:

$$\omega = \frac{0.622 \times \phi P_{sat}}{P - \phi P_{sat}} \quad (8)$$

Where  $P_{sat}$  is the saturation pressure. Note that  $\phi_4$  and  $T_4$  are given and  $P_4 = P_1$ . Having determined  $\omega_3$ ,  $T_3$  is determined by first calculating  $P_{sat,3}$ . Rearranging equation (8):

$$P_{sat,3} = \frac{\omega_3 P_3}{\phi_3 (0.622 + \omega_3)} \quad (9)$$

Note that  $\phi_3 = 100\%$  and  $P_3 \approx P_2$ .

With the conditions at the two intermediate points 2 and 3 determined, the cooling load ( $\dot{Q}_{cooling}$ ) and heating load ( $\dot{Q}_{heating}$ ) can be calculated from:

$$\dot{Q}_{cooling} = \rho Q (h_2 - h_3) - \dot{m}_w h_{L,3} \quad (10)$$

$$\dot{Q}_{heating} = \rho Q (h_4 - h_3) \quad (11)$$

Where  $\rho$  is the density,  $h$  the enthalpy per unit mass of dry air,  $\dot{m}_w$  the mass flow rate of condensed water vapour, and  $h_{L,3}$  the enthalpy of saturated liquid water at  $T_3$ . Enthalpy at any point is calculated from:

$$h = c_{pa} T + \omega \times (2500.9 \times 10^3 + c_{pv} T), \quad (12)$$

Where  $T$  is in  $^{\circ}\text{C}$  and  $c_{pa}$  and  $c_{pv}$  are the specific heat at constant pressure for dry air and water vapour, respectively. Following the usual practice, constant values of  $c_{pa} = 1005 \text{ J/kg}\cdot\text{K}$  and  $c_{pv} = 1820 \text{ J/kg}\cdot\text{K}$  are used in equation (12). The rate of condensed water-vapour ( $\dot{m}_w$ ) is calculated from:

$$\dot{m}_w = \dot{m}_a (\omega_2 - \omega_3) = \rho Q (\omega_2 - \omega_3) \quad (13)$$

Where  $\omega_2 = \omega_1$ , which can be calculated from equation (8) by using  $P_1$ ,  $P_{sat1}$  and  $\phi_1$ .

### Heat-transfer submodel to determine the rate of surface heat-transfer

The heating load, which adds significantly to the energy cost, can be minimized by allowing heat transfer from the warm surrounding air. Figure 3 shows the section of the duct where heat transfer with the surrounding takes place.

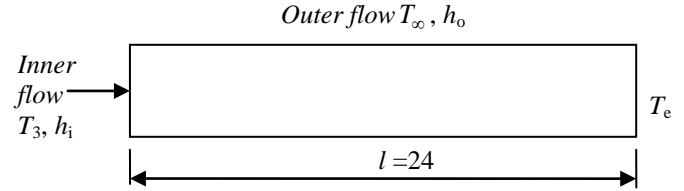


Figure 3. Section of the air duct where heat transfer takes place

If the rate of heat transfer from the surrounding air is  $\dot{Q}_{\infty}$ , the required heating load to be supplied by the heating coil ( $\dot{Q}_{coil}$ ) will be:

$$\dot{Q}_{coil} = \dot{Q}_{heating} - \dot{Q}_{\infty} \quad (14)$$

The rate of heat transfer from the surrounding air ( $\dot{Q}_{\infty}$ ), is calculated from:

$$\dot{Q}_{\infty} = \bar{U} A_s \Delta T_{lm} \quad (15)$$

Where  $\bar{U}$  is the overall heat transfer coefficient,  $A_s$  is the surface area of the duct ( $A_s = \pi D l$ ), and  $\Delta T_{lm}$  is the log-mean temperature difference defined as [11]:

$$\Delta T_{lm} = (T_3 - T_e) / \ln[(T_{\infty} - T_e) / (T_{\infty} - T_3)] \quad (16)$$

Where  $T_{\infty}$  is the temperature of the surrounding air, which is assumed to be constant along the duct. The exit temperature ( $T_e$ ) is obtained from the following equation:

$$T_e = T_{\infty} - (T_{\infty} - T_3) \times \exp\left(-\frac{\bar{U} A_s}{\dot{m} c_p}\right) \quad (17)$$

Where  $\dot{m}$  is the mass flow rate of air ( $\dot{m} = \rho Q = \rho V A_c$ ) and  $c_p$  is the specific heat of air at constant pressure.

Both equation (15) and (17) require the determination of the overall heat-transfer coefficient ( $\bar{U}$ ). For a thin-walled metal duct,  $\bar{U}$  is given by:

$$\bar{U} = \left( \frac{1}{h_i} + \frac{1}{h_o} \right)^{-1} \quad (18)$$

The heat transfer coefficient  $h_o$  provided by the outer natural flow is given as  $3 \text{ W/m}^2\cdot\text{K}$ . The inner heat-transfer coefficient  $h_i$  is determined from the Nusselt number ( $\text{Nu} = hD/k$ ), where  $k$  is the thermal conductivity of air. For the turbulent duct-flow,  $\text{Nu}$  is calculated from the Dittus-Boelter equation [9,11]:

$$\text{Nu} = 0.023\text{Re}^{0.8} \text{Pr}^n \quad (19)$$

Where  $\text{Pr}$  is the Prandtl number ( $\text{Pr} = c_p \mu / k$ ) and  $n = 0.4$  for heating and  $0.3$  for cooling. Fluid properties  $\mu$ ,  $c_p$ , and  $k$  are determined at the bulk mean temperature ( $T_b = (T_3 + T_4)/2$ ).

### Economic submodel to determine the total costs

Equation (5) and equation (14) yield the required power of the fan ( $\dot{W}_{fan}$ ) and the heating load on the coil ( $\dot{Q}_{coil}$ ) for the selected diameter of the duct. The energy cost ( $C_e$ ) of the duct for this diameter can then be obtained from:

$$C_e = (\dot{W}_{fan} + \dot{Q}_{coil}) \times t \times c_e / 1000 \quad (20)$$

Where  $t$  is the number of operating hours per day and  $c_e$  is the cost of electricity per kWh. The annual initial cost ( $C_i$ ) of the duct can be determined from:

$$C_i = N \times c_{id} / 15 \quad (21)$$

Where  $N$  is the number of prefabricated units used ( $N=L/0.9$ ),  $c_{id}$  is the cost of duct unit, and  $15$  is the expected lifetime of the duct. While the initial cost of the duct increases with increasing its diameter, the energy cost decreases due to lower friction and higher heat-transfer surface area. The optimum duct diameter is the one that minimises the total annual cost ( $C_t$ ):

$$C_t = C_i + C_e \quad (22)$$

### Evaluating thermal properties of air and water vapour

The above model involves a number of thermo-physical properties for air and water vapour. In order to apply the model to different conditions, these properties have to be calculated by Excel from respective equations. For example, air density ( $\rho$ ) is determined from the ideal-gas law ( $\rho = P/RT$ ). Other properties could also be calculated from equations obtained from the open literature or the internet. The specific heat ( $c_p$ ) for air can be obtained from the following equation [9]:

$$c_p = 10^3 \times (a + bT + cT^2 + dT^3) / M \quad (23)$$

Where  $T$  is in K,  $c_p$  is in J/kg.K, and the constants  $a$ ,  $b$ ,  $c$ ,  $d$  and  $M$  are  $28.11$ ,  $1.967 \times 10^{-3}$ ,  $4.802 \times 10^{-6}$ ,  $-1.966 \times 10^{-9}$ , and  $28.97$ , respectively. The dynamic viscosity of air ( $\mu$ ) can be determined from the Sutherland's formula [8]:

$$\mu = 1.45 \frac{T^{1.5}}{(T + 110) \times 10^6} \quad (24)$$

Where  $T$  is in K and  $\mu$  is in kg/m.s. Thermal conductivity ( $k$ ) of air can be obtained from the following equation [12]:

$$k = a + bT + cT^2 + dT^3 \quad (25)$$

Where  $T$  is in K and  $k$  is in W/m.K. For air, values of the constants  $a$ ,  $b$ ,  $c$ , and  $d$  are, respectively,  $-3.9333 \times 10^{-4}$ ,  $1.0184 \times 10^{-4}$ ,  $-4.8574 \times 10^{-8}$  and  $1.5207 \times 10^{-11}$ .

Water saturation pressure ( $P_{sat}$ ) in equation (8) can be approximated by the Antoine equation [10] as follows:

$$P_{sat} = 133.3 \times 10^{\left(\frac{a-b}{c+T}\right)} \quad (26)$$

Where  $T$  is in °C,  $P_{sat}$  in Pa, and the values of the three constants  $a$ ,  $b$ , and  $c$  are  $8.07131$ ,  $1730.630$ , and  $233.426$ , respectively. The saturation temperature for a given pressure can be determined by rearranging equation (26):

$$T = \frac{b}{a - \log_{10}(P_{sat} / 133.3)} - c \quad (27)$$

Equation (27) is needed for determining  $T_3$  from the known saturation pressure.

Replacing tabulated data of thermal properties by equations that are more suitable for computer calculations also gives students the opportunity to make use of Excel's trendline facility. Trendline can be used to curve-fit different types of functions to the tabulated data. For example, by entering the tabulated data [9] in the range ( $0^\circ\text{C} - 50^\circ\text{C}$ ) into Excel and fitting a linear trendline, the following equation is obtained for calculating the saturated-liquid enthalpy ( $h_L$ ) in equation (10):

$$h_L = 10^3 (4.184T + 0.146) \quad (28)$$

Where  $T$  is in °C and  $h_L$  in J/kg.

### EXCEL IMPLEMENTATION AND ANALYSIS

Since equations (1) to (28) are all explicit, they can be entered directly into Excel to determine the total cost ( $C_t$ ) for a selected diameter of the duct in the range  $0.1 \leq D \leq 0.6$  m. However, the unit cost ( $c_{id}$ ) in the calculation of the initial cost used in equation (21) has been changed manually for each  $D$ . To avoid this, the following Excel's If-function is used:

$$c_{id} = \text{IF}(D=0.1;8.99;\text{IF}(D=0.13;10.49;\text{IF}(D=0.15;11.49;\text{IF}(D=0.18;12.99;\text{IF}(D=0.2;14.49;\text{IF}(D=0.23;15.99;\text{IF}(D=0.25;16.99;\text{IF}(D=0.3;22.49;\text{IF}(D=0.35;30.99;\text{IF}(D=0.4;33.99;\text{IF}(D=0.46;39.99;\text{IF}(D=0.5;49.99;\text{IF}(D=0.55;55.99;\text{IF}(D=0.6;79.99;"D out of range" )))))))))))) \quad (29)$$

Table 2 shows the values of key properties as calculated by Excel for  $D = 0.2$  m. The table shows that a heating rate of more than  $3000 \text{ W}$  is needed in order to bring the air to the required condition. The table also shows that  $\dot{Q}_\infty = 594 \text{ W}$ , which amounts to nearly 19% of the required heating load.

Table 2: Calculated properties and quantities for  $D = 0.2$  m

Property	Equation	Value	Property	Equation	Value
Re	(2)	98749	$h_4$ [J/kg]	(15)	38696.2
$f$	(5)	0.0192	$\dot{m}_w$ [kg/s]	(17)	0.0076
$h_f$ [m]	(4)	7.7416	$\dot{Q}_{cooling}$ [W]	(13)	28261.9
$\dot{W}_{fan}$ [W]	(6)	21.8	$\dot{Q}_{heating}$ [W]	(14)	3127.1
$\omega_1$ [g/kg]	(9)	0.0338	Nu	(24)	198.10
$P_2$ [Pa]	(7)	100.0873	$h_i$ [W/m <sup>2</sup> .K]	(23)	25.0163
$T_2$ [°C]	(8)	40.0781	$T_e$ [°C]	(21)	12.0212
$\omega_4$ [kg/kg]	(9)	0.0073	$\dot{Q}_\infty$ [W]	(19)	593.87
$T_3$ [°C]	(12)	9.3132	$C_i$ [\$]	(28)	26.83
$h_2$ [J/kg]	(15)	127204.0	$C_e$ [\$]	(27)	746.08
$h_3$ [J/kg]	(15)	27813.3	$C_t$ [\$]	(29)	772.91

Four scenarios were considered for determining the optimum duct diameter ( $D_o$ ) as shown in Table 3. The four cases represent different possible scenarios as specified in the design case. In case (B), the cost of electricity was increased to 0.2\$per kWh, which doubles the cost of energy. Note that, doubling the cost of electricity at 8 operating hours per day has the same effect as doubling the operating hours per day at 0.1 \$per kWh. In case (C), the operating hours were reduced to 4 hours per day, which reduces the energy consumption and cost. In case (D), only the fan power was considered in the calculation of the energy cost. This would be the case if heating the air was not necessary or if the heating load was provided by another source of energy.

Table 3: Scenarios for determining the optimum duct diameter

Case	Cost of electricity \$/kWh	Daily operating hours	Electricity consumption
A	0.10	8	Fan + heating coil
B	<b>0.20</b>	8	Fan + heating coil
C	0.10	<b>4</b>	Fan + heating coil
D	0.10	8	<b>Fan only</b>

Figure 4 shows the variation of the annual initial, energy, and total costs calculated for each of the four cases at different diameters of the duct. Approximate estimates of the optimum diameters for the four cases could be obtained from Figure 4 by visual inspection, but exact values have to be determined by using Excel's add-in "Solver". Although equation (29) gives exact values of the unit cost at the diameters specified in Table 1, it fails to produce the cost for intermediate diameters as required by Solver. This problem can be solved by calculating  $c_{id}$  from the following continuous function developed by

making use of Excel to fit a trendline on the data shown in Table 1:

$$c_{id} = 600.3D^3 - 383.1D^2 + 147.8D - 3.819 \quad (30)$$

With equation (28) as a target function for optimisation, Solver was used to determine the optimum diameter for each of the four scenarios shown in Table 3. For case (A) the minimum total cost was obtained at  $D_o = 0.429$  m. At this diameter,  $\dot{Q}_\infty$  is 968.6W, which is about 31% of the total heat load. In case (B),  $D_o$  increased to 0.493 m and  $\dot{Q}_\infty$  increased to 1020W. For case (C),  $D_o$  reduced to 0.36 m and  $\dot{Q}_\infty$  decreased to 891W. In case (D), for which only the fan power was considered,  $D_o$  reduced to 0.21 m, which reduces the initial cost of the duct to about half its value at case (A).

### VBA USER-DEFINED FUNCTIONS

Developing user-defined functions (UDFs) with VBA is useful in Excel implementation when the same function is frequently used in the calculations. For example, UDFs can be developed for the calculation of enthalpy (Equation 12) and water saturation pressure (Equation 26). For heat-transfer calculations, UDFs can be developed to determine the specific-heat (Equation 23), viscosity (Equation 24), and thermal conductivity (Equation 25). Such UDFs minimise the development effort of the Excel sheet while improving its user-friendliness, clarity, and maintainability. Moreover, in certain situations, UDFs become necessary in order to overcome the limitation of spreadsheet calculations. A good example of this situation is given by the calculation of the initial cost of the duct unit ( $c_{id}$ ) from equations (29) and (30).

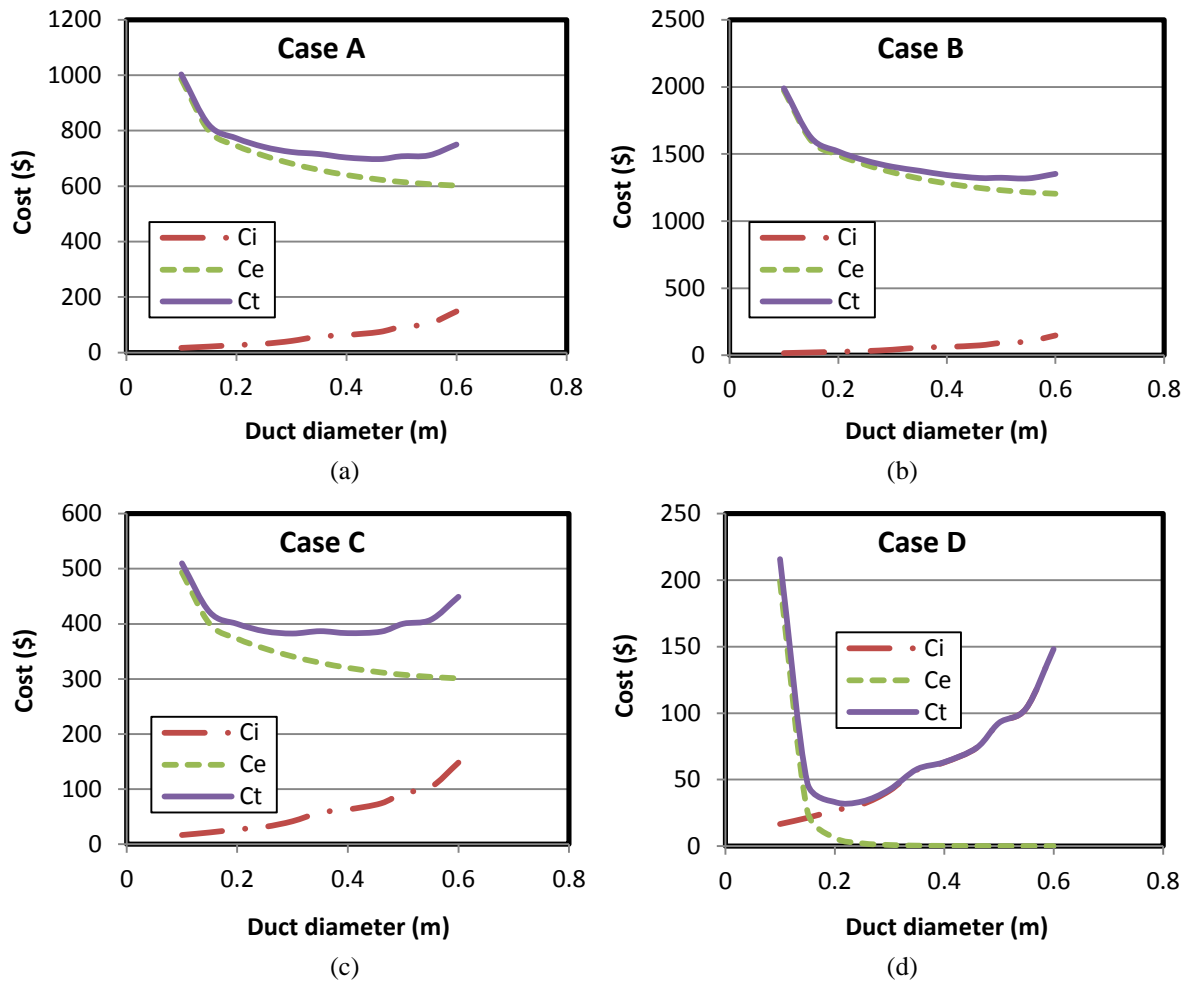


Figure 4. Variation of costs with duct diameter for the different scenarios shown in Table 3

Equation (30) was developed because equation (29), which does not provide a continuous function in  $D$ , could not be used in conjunction with Solver in order to determine the optimum diameter. Figure 5 compares the unit cost as calculated by equation (30) with the exact values shown on Table 1. As the figure shows, values obtained from the third-order polynomial function deviate from the exact values at certain diameters. A degree of inaccuracy persists even if a higher-order polynomial is used. This should be expected as the unit cost is not a simple function of its diameter, but depends on other factors such as the gauge and the demand on a particular diameter. Although inexact, equation (30) provides a continuous function and, therefore, had to be used in conjunction with Solver. This restriction of the spreadsheet can be overcome by developing the two UDFs, called "cid" and "Interpoll" shown in the Appendix. The UDF "Interpoll" returns the exact cost values for the diameters shown on Table 1 (refer to Figure 5) while interpolating between adjacent data when the diameter falls in between, as required by Solver.

The interpolation function "Interpoll" is actually a general-purpose function that can be used for linear interpolation of any tabulated data. For example, it can be used to determine  $P_{sat}$ ,  $h_L$ , or Pr from tabulated data. In this case also, the interpolation

function yields more accurate estimations than an equation obtained by fitting a trendline.

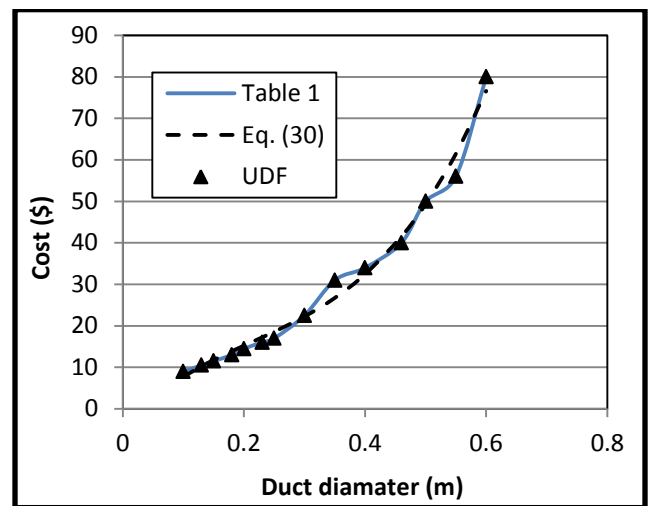


Figure 5. Accuracy of unit cost calculations by Equation (30) and VBA user-defined function

## CONCLUSION

The process of selecting the duct's diameter for an air-conditioning system poses an optimisation problem the solution of which requires applying the principles of thermodynamics, fluid dynamics, heat transfer, and economics. The present paper presents a case which is suitable for introducing thermal-design optimisation to engineering students and provides the equations needed for its computer-aided analysis. Since all the equations are explicit, they can be entered easily into Excel so that all the calculations involved can be done by using only its built-in functions. Excel trendline can be used to develop equations for thermal properties of atmospheric air while Excel's add-in "Solver" can be used to determine the optimum diameter of the duct at different scenarios.

VBA makes Excel a powerful modelling platform for engineers by developing user-defined functions. In the present design case the fluid involved is air, for which properties depend on temperature only or could be obtained from the ideal-gas law. This minimised the need for developing property functions with VBA. Had the fluid been water, refrigerant, or any other fluid that passes through phase-change, then it is most likely that the case would not be analysed without extensive use of VBA functions. The VBA function "Interpoll" presented here is a general-purpose function that can be used by Excel users for linear interpolation of their tabulated data.

Using Excel with VBA as a modelling platform in engineering education is particularly helpful for engineering institutes in developing countries which lack the funds needed to acquire dedicated software. Therefore, this combination deserves more attention in the development of engineering curricula in these countries.

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## Appendix: User-Defined Functions

Function cid(D)

Dim DD, CC As Variant

DD = Array(0.1, 0.13, 0.15, 0.18, 0.2, 0.23, 0.25, 0.3, 0.35, 0.4, 0.46, 0.5, 0.55, 0.6, 0.65)

CC = Array(8.99, 10.49, 11.49, 12.99, 14.49, 15.99, 16.99, 22.49, 30.99, 33.99, 39.99, 49.99, 55.99, 79.99, 89.99)

Ndata = 15

cid = Interpoll(D, DD, CC, Ndata)

End Function

Function Interpoll(T, TT, PP, Ndata)

' General-purpose linear interpolation function

' TT is the independent variable, PP the dependent variable,

' Ndata the total number of data points, and T the given value

N = Ndata - 1

i = 0

flag = 0

Do While flag = 0 And i < N

If T = TT(i) Then

Interpoll = PP(i)

flag = 1

ElseIf (T > TT(i) And T < TT(i + 1)) Then

Interpoll = PP(i) + (T - TT(i)) / (TT(i + 1) - TT(i)) \* (PP(i + 1) - PP(i))

flag = 1

End If

i = i + 1

Loop

If T = TT(N) Then

Interpoll = PP(N)

flag = 1

End If

If flag = 0 Then

Interpoll = "Given data is out of range"

End If

End Function