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Development of A Process for Predicting the Overall Heat Transfer Coefficient for Transient Heat Transfer in An Exhaust System using CFD

B. Anitha Reddy, B. Harish Babu, G. Chitti Babu, B. Chandrakala

Abstract: The analysis of heat transfer of automotive exhaust system is most important since their prominence in the design and also in the optimization phase of exhaust after treatment system.This paperdeals with the process which can be useful to predict the overall heat transfer coefficient for the transient flow of pipe in the after treatment system. This considers the convection of heat along gas flow, the convection between gas and wall, conduction through wall, radiation and of course convection to the ambient. Governing equations are obtained for the transient flow in a pipe for calculating gas temperature and wall temperature at distance x and time t. Analytical solution will be computed using CFD techniques for these governing equations. From the obtained analytical solution to the transient flow in pipe an excel tool will be developed which can be able to give the outlet temperature of the pipe in transient flow at length x and time t, total heat loss from pipe to the ambient, overall heat transfer coefficient for the pipe.

Keywords: CFD, Excel tool, Gas temperature, Transient pipe flow, Wall temperature.

I INTRODUCTION

Thermal behavior of automotive exhaust system is prominent in the engine design for two main reasons. One is that the exhaust system component's durability and other related under-hood components which are affected by the high temperature. The other is that the catalyst light-offtime [1]. Based on the stringent emissions regulations, quick catalyst light-off time has become a crucial requirement in engine combustion and in the development of exhaust systems.So many efforts have been made towards the front end of the exhaust to minimize the total heat loss from exhaust gases to the components prior to catalyst for ensuring the minimization of the catalyst light-off time. Exhaust system components plays an important role in the heat release in the under hood environment [2].

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* Correspondence Author

B. Anitha Reddy*, Department of Applied Engineering, Vignan's Foundation for Science, Technology and Research University, Vadlamudi, India.

B. Harish Babu , Department of Applied Engineering, Vignan's Foundation for Science, Technology and Research University, Vadlamudi, India.

G. Chitti Babu, Department of Mechanical Engineering, Vignan's Foundation for Science, Technology and Research University, Vadlamudi, India.

B. Chandrakala, Department of Automobile Engineering, Godavari Institute of Engineering and Technology, Rajahmundry, India.

Hence, minimizing the temperature of the exhaust components can greatly increase the durability and also reduce the cost of exhaust and other related under hood components. Another reason for the thermal management is to improve efficiency of the catalytic converter, especially during cold start. A computermodel to estimatethe exhaust component and gas temperatures is very important for exhaust system design. To estimate the converter conversion previously requires the gas' temperature entering a converter. A thermal model used to predict temperature of the gas entering a converter is of high importance. performance [3], the models which are developed

II. HEAT TRANSFER ANALYSIS IN 1 D TRANSIENTFLOW IN PIPE

A. *Transient flow in pipe*

The phenomenon of heat transfer of an automotive exhaust system is relatively complex to observe and model.Forced heat convection is observed inside of the component surfaces. Also commonly radiation and natural heat convection exist outside of the componentsurfaces. For making the use of finite element software, the parameters which have to be known for the each cross section are, the convective heat coefficient based on the gas flow and temperature of the exhaust gas. For most of the cases, one of the unknown parameter will be temperature of the exhaust gases. That is why, this problem can be solved using a practical approach for making use in the engineering applications. CFD (Computational Fluid Dynamics) software is a very effective and suitable tool and is a solution for the above problem, but the complete exhaust system is very costly to develop the model and solve by considering the model size and nonlinear nature of the problem. Hence, a simple analytical approach is needed to simulate the heat transfer analysis in exhaust system, whose result can be used as the boundary condition in the structural analysis.

B. *Governing equations*

During the engine cold start, the exhaust gas wall temperature will not be constant as it is continuously heated up by exhaust gas. The warming up of the wall is greatly affected by the internal heat transferred from the exhaust gases, external heat transfer to surroundings, its properties and thermal mass.

Also, warming up of the wall will change the thermal boundary conditions and influence the temperature of the outlet gas.In the transient state of condition, both the wall and gas temperature vary along with the position and the time as replicated in figure 2.1.By considering the energy conservation, the below partial differential equations are obtained for wall and gas respectively.

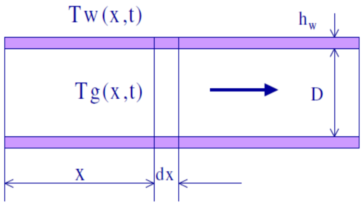

Figure 1.1 D transient flow in pipe

i. Governing equation for gas

$$\frac{1}{4}\pi D^2 \rho C_v \frac{\partial T_g}{\partial t} = -h_i \pi D\left(T_g - T_w\right) - \dot{m} C_p \frac{\partial T_g}{\partial x} \qquad (1)$$

ii. Governing equation for gas wall

$$C_w \rho_w (t_w^2 + D t_w)\frac{\partial T_w}{\partial t} = h_i D\left(T_g - T_w\right) - h_o(D + 2t_w)\left(T_g - T_a\right)$$

$$-\varepsilon_w \sigma (D + 2t_w)(T_w^4 - T_a^4) + k_w (t_w^2 + D t_w)\frac{\partial^2 T_w}{\partial x^2}$$

C. Solution to partial differential equations

The below equation shows the basic form of partial differential equation (applicable up to the 2nd order) is

$$a\frac{\partial^2 F(x,t)}{\partial x^2} + b\frac{\partial^2 F(x,t)}{\partial x\,\partial y} + c\frac{\partial^2 F(x,\ t)}{\partial y^2} + d\frac{\partial F(x\,,y)}{\partial x} + e\frac{\partial F(\,x,y)}{\partial y} + f = 0 \qquad (3)$$

Where the appeared coefficients a to fare functions of **y**and x. Even, a particularform of differential equation can be much simple onethan equation (3). Depending on thegiven coefficients a, ***b*** and c, a partial differential equation can be classified ashyperbolic, parabolic, or elliptic. Apartial differential equation can be hyperbolic when b^2- 4ac > 0, parabolic when b^2- 4ac = 0,elliptic when b^2-4ac < 0. In some special cases the space coordinate y is replaced with the time t. The above given equation (1) is a 1st order hyperbolic form of partial differential equation and equation (2) is a 2nd order parabolic form of partial differential equation. The solution to both hyperbolic and parabolic partial differential equations is discussed below.

D. Solution to Second Order Parabolic Partial Differential Equations

A 2nd order parabolic form of partial differential equation with respect to time and space can be in the form of

$$\frac{\partial F}{\partial t} = a\frac{\partial^2 F}{\partial x^2}$$

Where F is the function of t and x, a is constant which does not depend on the coordinates t and x.The following methods help to solve the second order parabolic form of partial differential equations.

i. ExplicitCFD Methods

(a) FTCS METHOD (Forward difference in time and central difference in space)

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \quad , \quad \frac{\partial^2 F}{\partial x^2} = \frac{F_{x+1}^t - 2F_x^t + F_{x-1}^t}{(\Delta x)^2}$$

(b) RICHARDSON METHOD

$$\frac{\partial F}{\partial t} = \frac{F_x^{\,t+1} - F_x^{\,t-1}}{2(\Delta t)} \quad , \quad \frac{\partial^2 F}{\partial x^2} = \frac{F_{x+1}^{\,t} - 2F_x^t + F_{x-1}^{\,t}}{(\Delta x)^2}$$

(c) DUFORT-FRANKEL METHOD

$$\frac{\partial F}{\partial t} = \frac{F_x^{\,t+1} - F_x^{\,t-1}}{2(\Delta t)} , \frac{\partial^2 F}{\partial x^2} = \frac{F_{x+1}^{\,t} - 2\frac{(F_x^{\,t+1} + F_x^{\,t-1})}{2} + F_{x-1}^{\,t}}{(\Delta x)^2}$$

ii. Implicit Method

(a) LAASONEN METHOD

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \quad , \quad \frac{\partial^2 F}{\partial x^2} = \frac{F_{x+1}^{t+1} - 2F_x^{t+1} + F_{x-1}^{t+1}}{(\Delta x)^2}$$

(b) CRANK-NICOLSON METHOD

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)}$$

$$\frac{\partial^2 F}{\partial x^2} = \frac{1}{2}\left[\left(\frac{F_{x+1}^{t+1} - 2F_x^{t+1} + F_{x-1}^{t+1}}{(\Delta x)^2}\right) + \left(\frac{F_{x+1}^t - 2F_x^t + F_{x-1}^t}{(\Delta x)^2}\right)\right]$$

(c) β-FORMULATION

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)}$$

$$\frac{\partial^2 F}{\partial x^2} = \left[\beta\left(\frac{F_{x+1}^{t+1} - 2F_x^{t+1} + F_{x-1}^{t+1}}{(\Delta x)^2}\right) + (1 - \beta)\left(\frac{F_{x+1}^t - 2F_x^t + F_{x-1}^t}{(\Delta x)^2}\right)\right]$$

Where F_x^t is taken as the identity of the function F at distance x and time t. β is a constant which does not depend on t and x.

E. Solution to first order hyperbolic form of partial differential equations

A 1st order hyperbolic from of partial differential equation with respect to space and time can be written in the form of

$$\frac{\partial F}{\partial t} = a\frac{\partial F}{\partial x}$$

Where F is the function of t and x, a is constant which is not a function of t and x.The following methods help to solve the 1st order hyperbolic form of partial differential equations.

i. FTCS Method

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \quad , \quad \frac{\partial F}{\partial x} = \frac{F_{x+1}^t - F_{x-1}^t}{2(\Delta x)}$$

ii. FTFS Method

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \quad , \quad \frac{\partial F}{\partial x} = \frac{F_{x+1}^t - F_x^t}{(\Delta x)}$$

iii. FTBS Method

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \;, \quad \frac{\partial F}{\partial x} = \frac{F_x^t - F_{x-1}^t}{(\Delta x)}$$

iv. IMPLICIT Method

$$\frac{\partial F}{\partial t} = \frac{F_x^{t+1} - F_x^t}{(\Delta t)} \;, \quad \frac{\partial F}{\partial x} = \frac{F_{x+1}^{t+1} - F_{x-1}^{t+1}}{2(\Delta x)}$$

F. Solving Gas Equation Using FTFS Explicit Method

The Explicit FTFS method is used to solve hyperbolic gas temperature equation, due to its simplicity and less complexity in the solution. FTFS method decomposes a partial differential equation into finite difference elements.Now the equation (1) can be written as

$$a\frac{\partial T_g}{\partial t} + b\left(T_g - T_w\right) + c\frac{\partial T_g}{\partial x} = 0 \qquad (3)$$

Where $a = \frac{1}{4}\pi D^2 \rho C_v, \quad b = h_i \pi D, \quad c = \dot{m} C_p$

Now the equation (3) can be interpreted in terms of finite differences as shown below

$$a\frac{T_{g_x}^{t+1} - T_{g_x}^{t}}{(\Delta t)} + b\left(T_{g_x}^{t} - T_{w_x}^{t}\right) + c\frac{T_{g_{x+1}}^{t} - T_{g_x}^{t}}{(\Delta x)} = 0 \qquad (4)$$

$$T_{g_x}^{t+1} = \frac{T_{g_{x-1}}^{t} + T_{g_{x+1}}^{t}}{2} \qquad (From\ [6])$$

Equation (4) can be written as

$$\left(\frac{a}{2(\Delta t)} + \frac{c}{(\Delta x)}\right)T_{g_{x+1}}^{t} = \left(\frac{a}{(\Delta t)} - b + \frac{c}{(\Delta x)}\right)T_{g_x}^{t} - \frac{a}{2(\Delta t)}T_{g_{x-1}}^{t} + bT_{w_x}^{t}$$

$$T_{g_{x+1}}^{t} = iT_{g_x}^{t} + jT_{g_{x-1}}^{t} + sT_{w_x}^{t} \qquad (5)$$

$$i = \frac{2[a(\Delta x) - b(\Delta x \Delta t) + c\,(\Delta t)]}{a(\Delta x) + 2c\,(\Delta t)} \,,$$

$$j = -\frac{2a(\Delta x)}{a(\Delta x) + 2\,c(\Delta t)} \;, \quad s = \frac{2b(\Delta x \Delta t)}{a(\Delta x) + 2c(\Delta t)}$$

G. Solving Wall Equation Using FTCS Explicit Method

The Explicit FTCS method is used to solve parabolic wall temperature equation, due to its simplicity and less complexity in the solution. FTCS method decomposes a partial differential equation into finite difference elements. Now the equation (2) can be written as

$$z\frac{\partial T_w}{\partial t} = e\frac{\partial^2 T_w}{\partial x^2} + f\left(T_g - T_w\right) - g\left(T_w - T_a\right) - p(T_w^4 - Ta4(6)$$

Where z, e, f, g, p can be given by

$$z = C_w \rho_w (t_w^2 + Dt_w)\,, \quad e = k_w(t_w^2 + Dt_w)\,, f = h_i D,$$

$$g = h_o(D + 2t_w), \qquad p = \varepsilon_w \sigma (D + 2t_w)$$

Now the equation (6) can be interpreted in terms of finite differences as shown below

$$z\frac{T_{w_x}^{t+1} - T_{w_x}^{t}}{(\Delta t)} = e\frac{T_{w_{x+1}}^{t} - 2T_{w_x}^{t} + T_{w_{x-1}}^{t}}{(\Delta x)^2} + f\left(T_{g_x}^{t} - T_{w_x}^{t}\right) - g\left(T_{w_x}^{t} - T_a\right) - p\left(T_{w_x}^{t\,4} - T_a^4\right) \qquad (7)$$

$$T_{w_x}^{t+1} = \frac{T_{w_{x-1}}^{t} + T_{w_{x+1}}^{t}}{2} \qquad (From\ [6])$$

Equation (7) can be written as

$$\left(\frac{z}{2(\Delta t)} - \frac{e}{(\Delta x)^2}\right)T_{w_{x+1}}^{t} - \left(\frac{z}{(\Delta t)} - \frac{2e}{(\Delta x)^2} - (f+g)\right)T_{w_x}^{t} + \left(\frac{z}{2(\Delta t)} - \frac{e}{(\Delta x)^2}\right)T_{w_{x-1}}^{t} + pT_{w_x}^{t\,4} - fT_{g_x}^{t} - (gT_a + pT_a^4) = 0 \qquad (8)$$

$$T_{w_{x+1}}^{t} = nT_{w_x}^{t} - T_{w_{x-1}}^{t} - uT_{w_x}^{t\,4} + vT_{g_x}^{t} + y$$

$$n = \frac{2\,[z\,(\Delta x)^2 - 2e(\Delta t) - (f+g)(\Delta t)(\Delta x)^2]}{z(\Delta x)^2 - 2e(\Delta t)} \,,$$

$$u = \frac{2p(\Delta t)(\Delta x)^2}{z\,(\Delta x)^2 - 2\,e\,(\Delta t)}$$

$$v = \frac{2\,f\,(\Delta t)(\Delta x)^2}{z\,(\Delta x)^2 - 2\,e(\Delta t)} \,,$$

$$y = \frac{2(gT_a + pT_a^4)(\Delta t)(\Delta x)^2}{z\,(\Delta x)^2 - 2e(\Delta t)}$$

For solving the above finite difference element equations one need to have initial boundary conditions along with the gas, pipe and ambient characteristic parameters. Initial assumptions are also included to get the final output values.

H. Initial Boundary Conditions

The below mentioned initial boundary conditions are sufficient to solve the two transient flow equations (1) and (2)for the two unknowns i.e., wall and gas temperature.

1. Gas Outlet Temperature = Tout(x,t)2. Pipe Wall Temperature = Tw(x,t)

<u>Initial assumptions to solve transient flow PDEs:</u>

Pipe inlet temperature at x=0 and t=0 = $Tg_{(x=0,\, t=0)} = T_{in}$

Pipe inlet temperature at x=-1 and t=0 = $Tg_{(x=-1,t=0)} = T_{in}$

Wall temperature at x=0 and t=0 = $Tw_{(x=0,\, t=0)} = T_w$

Wall temperature at x=-1 and t=0 = $Tw_{(x=-1,\, t=0)} = T_w$

In many heat transfer analysis models for the exhaust systems, hereonly energy conservation equations were employed, assumptions must be made in order to get a solution, even thoughtheseassumptions were not compulsorily mentioned.Though, the difficulty of solution algorithm is highly loweredbecause of these assumptions, and enough accuracy isobserved for the heat transfer analysis.

I. *Heat Transfer Formulas Used In Calculation*

$$Re = \left(\frac{4}{\pi\mu}\right)\frac{\dot{m}}{D}$$

$$Pr = \frac{C_p\mu}{k}$$

Heat transfer coefficient for inside pipe flow (Force convection heat transfer)

$$\mathrm{Nu_i} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.3} \quad (from\ [5])$$

$$\mathrm{h_i} = \mathrm{Nu_i}\frac{k}{D_i}$$

Heat transfer coefficient for outside pipe flow (Natural Convection Heat transfer):

To calculate outside heat transfer coefficient Churchill and Chu have givenone simple correlation for large range of Rayleigh number. The correlation can be given as

$$Nu_o = \left(0.6 + \frac{0.387Ra^{\frac{1}{6}}}{\left(1+\left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 (Valid\ for\ R < 10^{12})$$

$$\mathrm{h_o} = \mathrm{Nu_o}\frac{k}{D_o}$$

Heat loss from the pipe (Q):

$$Q = \dot{m}C_p(T_{in} - T_{out})$$

For calculating the overall heat transfer coefficient for the pipe, one should use conservation ofenergy in the pipe i.e.,

Heat lost in the pipe from inlet to outlet = Heat lost from the pipe to ambient i.e.,

$$\dot{m}C_p(T_{in} - T_{out}) = U_oA_s(T_{in} - T_a)$$

$$U_o = \frac{Q}{A_s(T_{in} - T_a)}$$

Where A_s= Heat Transfer surface area of the pipe (outer surface area of pipe)

U_o= Overall HTC of the pipe

III. RESULTS AND DISCUSSIONS

With the following input data, from the excel tool which has been developed with the help of solutions to the transient state partial differential equations of the given pipe flow. Some of the observations made will be as follows.

The inputs to the tool are as follows:

D = 0.12 m, L= 0.75 m, t = 15 mm, Ta = 298 K, mass flow rate = 0.0167 Kg/s, Tw = 298 K. Also some of the properties of the pipe also have been taken into consideration.

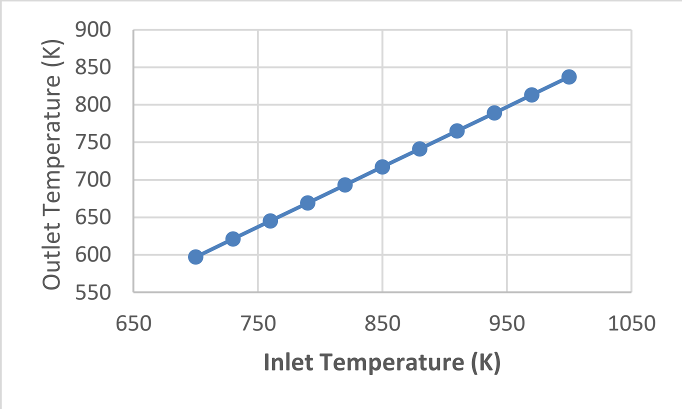

Figure 2. Effect of inletgas temperature on outlet gas temperature

The above graph shows the graph of outlet temperature of the gasvs inlet input temperature given to the tool.The values are observed to be in the range of 14 to 16% of the inlet gas temperature. As mentioned earlier the loss of temperature in including the conduction, convection and radiation processes of the exhaust gases.Also the overall heat transfer of the pipe can be calculated by the tool.

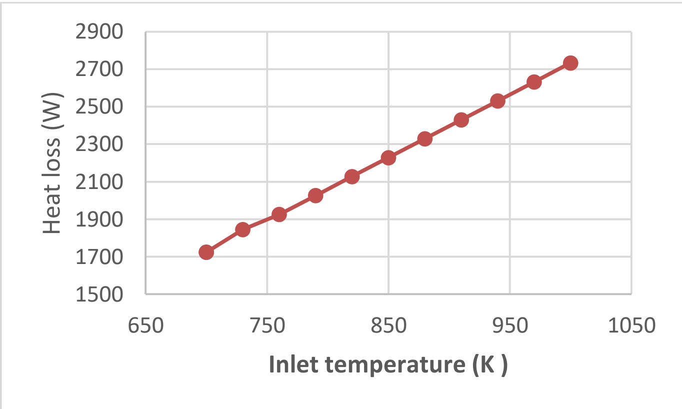

Figure 3. Effect of inlet temperature on Heat lost from the pipe

The above graph shows the effect of inlet gas temperature on heat lost from the exhaust gases to the surroundings.As the inlet temperature rises the heat lost rate from the pipe is observed to be less variant. So, higher the temperature comparatively lower the rate of heat loss. Also, from the dynamic experimental values can be obtained through the various tests and can be compared for the effective monitoring of the tool. The analysis results can also be variable with the parameters such as characteristics of the pipe material, ambient and exhaust gases.

IV. CONCLUSIONS

The analytical solution for the partial differential equations of transient flow governing equations is obtained by computational fluid dynamic techniques.An excel tool is developed with the help of analytical solution to the transient flow in pipe.The excel tool is able to give the outlet gas temperature of the pipe, the total heat lost to the ambient and overall heat transfer coefficient.

The excel tool can able to include the characteristic effect of heat conduction through the wall, convection between the gas and wall, convection along the gas flow in pipe, radiation and convection to the ambient on the outlet temperature of the pipe, the total heat lost to the ambient and overall heat transfer coefficient.

APPENDIX

COMPUTATIONAL HEAT TRANSFER (VBA CODE) [9,10]

```
Dim i As Double, Dim j As Double, Dim s As Double
Dim n As Double, Dim u As Double, Dim v As Double
Dim y As Double, Dim x As Double, Dim t As Double
Dim TG() As Double, Dim TW() As Double, Dim Tino As Double
Dim Two As Double, Dim Ta As Double, Dim a As Integer
Dim b As Integer, Dim Tout As Double, Dim Cp As Double
Dim MFR As Double, Dim Q As Double, Dim Uo As Double
Dim D As Double, Dim w As Double, Dim L As Double
Private Sub cmdCal_Click()
Tino = Cells(6, "D").Value
Two = Cells(8, "D").Value
i = Cells(23, "I").Value
j = Cells(24, "I").Value
s = Cells(25, "I").Value
n = Cells(14, "L").Value
u = Cells(15, "L").Value
v = Cells(16, "L").Value
y = Cells(17, "L").Value
x = Cells(24, "D").Value
t = Cells(26, "D").Value
Cp = Cells(14, "D").Value
D = Cells(3, "D").Value
w = Cells(5, "D").Value
MFR = Cells(13, "D").Value
Ta = Cells(7, "D").Value
L = Cells(4, "D").Value
ReDim TG(t, x) As Double
ReDim TW(t, x) As Double
For a = 0 To t
For b = 0 To x
If (a = 0 And b = 0) Then
TG(a, b) = Tino
TW(a, b) = Two
ElseIf (a <> 0 And b = 0) Then
TG(a, b) = (TG(a - 1, b) + TG(a - 1, b + 1)) / 2
TW(a, b) = (TW(a - 1, b) + TW(a - 1, b + 1)) / 2
ElseIf b = 1 Then
TG(a, b) = (i * TG(a, b - 1)) + (j * TG(a, b - 1)) + (s * TW(a, b - 1))
TW(a, b) = (n * TW(a, b - 1)) - TW(a, b - 1) - (u * (TW(a, b - 1)) ^ 4) + (v * TG(a, b - 1)) + y
ElseTG(a, b) = (i * TG(a, b - 1)) + (j * TG(a, b - 2)) + (s * TW(a, b - 1))
TW(a, b) = (n * TW(a, b - 1)) - TW(a, b - 2) - (u * (TW(a, b - 1)) ^ 4) + (v * TG(a, b - 1)) + y
End If
Next b
Next a
Tout = TG(t, x)
Q = MFR * Cp * (Tino - Tout)
Uo = Q / (3.14 * (D + (2 * w) * L * (Tino - Ta)))
Range("O6").Value = Tout
Range("O7").Value = Q
Range("O8").Value = Uo
End Sub
```

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