LS-DYNA Pipe Network Flow Analyzer

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Objective

Calculate the flow rate and convection heat transfer coefficient in each flow passage in the tools for the hot stamping manufacturing process.

Introduction

The tools must be cooled in the hot stamping manufacturing process. The geometry of the cooling passages in the tools runs the gamut from straight single pass pipes to pipes with branches and flow patterns that follow the shape of the stamping. One approach is to use a CFD code to calculate the flow velocity and predict a convection heat transfer coefficient. This heat transfer coefficient, h, is then used in a coupled thermal-stress calculation to predict die cooling and the effect of the cooling rate on the stamping. The advantage of Navier-Stokes CFD is that h is calculated at every node point and can vary with radial and axial position. The accuracy depends on the fineness of the mesh to capture the boundary layer in order to predict a reliable value for h. The main disadvantage is that as the mesh is refined the CPU time increases and may become prohibitive.

An alternative approach it to use a pipe network flow analyzer. This approach is based on an overall energy and mass balance. An average value for h is predicted for the pipe segment. This is a very quick computation and our future plan is to embed this in LS-PrePost with a GUI.

Think about the pipes in your house. The starting point is the valve on the pipe entering your house. We will call this NODE 1. NODE 1 is special and has a boundary condition specified. This BC is the pressure you would read on a pressure gauge attached to the valve or the water volumetric flow rate. The water enters your house and passes through several fittings (e.g., elbows and tees) before it exits through the faucet in your sink. Every pipe fitting is represented by a node. The node representing the faucet is special in that a pressure BC must be specified. The pipe flow code will calculate the pressure at the intermediate junction (fitting) nodes and the flow rate through each pipe. The convection heat transfer coefficient is then calculated for each pipe.

In water hydraulics we use the term "head" as a pressure measurement in units of feet or meters. "Head" can be converted to pressure units of Pa or psi which you are probably more familiar with. However, we need to make a distinction between thermodynamic pressure and the elevation of pipes above the ground. The equations simplify if we add thermodynamic pressure (converted from Pa to m) and elevation (m). This is known as the "total head".

Theory - Pipe Flow

For non-horizontal pipes, the energy equation (i.e, Bernoulli equation) is applied to the two end sections of the pipe, and the loss term, h_f (i.e, friction) is included; thus

$$\left(\frac{V_1^2}{2g}+\frac{P_1}{\rho g}+z_1\right)-\left(\frac{V_2^2}{2g}+\frac{P_2}{\rho g}+z_2\right)=h_f$$

P = thermodynamic pressure at a point

V = fluid flow velocity at a point

z = the elevation of point above a reference plane

h_f = loss term due to friction

We typically think of pressure defined in units of Pa or psi. However, in water hydraulics we use the nomenclature of "head" for pressure from the empirical science of hydraulics developed in the 19th century. Note that the units for each term in the Bernoulli equation (eq. 1) are length (e.g., m, ft). We refer to each term as a "head" which represents the pressure exerted by a liquid column of water of that height. If we multiply each term by ρg, then we obtain units of pressure in Pa (or psi).

- The velocity head, $V^2/2g$, represents the energy of the fluid due to its bulk motion. I'm sure as a child you made use of this "velocity head" as you directed the spray of a garden hose at the ground and drilled a hole or gully in the dirt. This is the kinetic energy of bulk fluid motion.
- The pressure head, $P/\rho g$, is the thermodynamic pressure of a fluid exerting a force on its container due to internal molecular motion.
- The elevation head, z, represents the potential energy of the fluid in terms of height.
- The static head (also called piezometric head, hydraulic head) is the sum of the pressure head and elevation head, $P/\rho g+z$. This is the pressure you would see on a pressure gauge at the location z.
- The total head is the sum of the velocity head and the static head (i.e., the summation within the parenthesis in eq. 1).
- The head loss, h_f, (also called friction head, resistance head) is the difference between the total head at 2 points (calculated using eq. 1) due to the friction forces acting against a fluid's motion by the pipe wall. In practice, we typically add other minor losses (e.g., pipe fittings, pipe size transitions) to this term.

The Bernoulli equation can be rearranged as follows

$$\left(\frac{V_1^2-V_2^2}{2g}\right)+\left(\frac{P_1-P_2}{\rho g}\right)+(z_1-z_2)=h_f$$

A useful equation relating volumetric flow rate, Q [m^3/sec], to flow velocity, V, is

$$Q=AV$$

where A is the pipe cross sectional area.

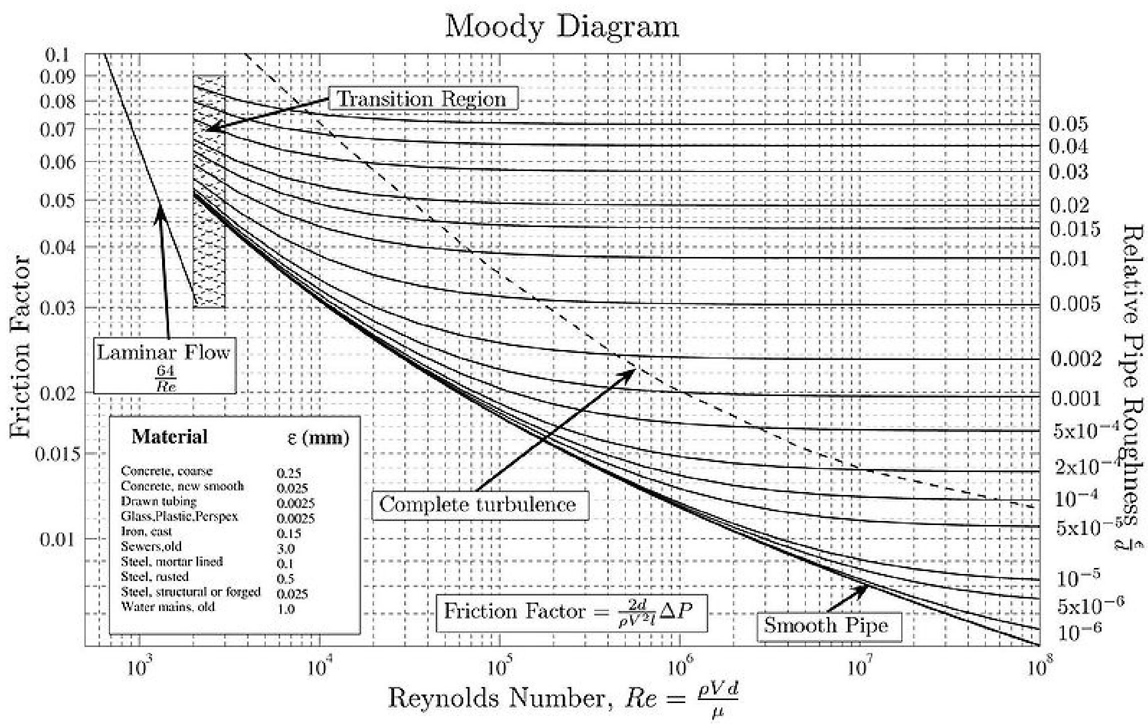
WARNING

Q is the volumetric flow rate in units of [m^3/sec]. Do not confuse it with the mass flow rate, $\dot{m} = \rho Q$, in units of [kg/sec].

An equation for the friction loss term, h_f, is available from experimental results and utilizing dimensional analysis as an aid in correlating the data.

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = f \frac{L}{D^5} \frac{8Q^2}{g\pi^2}$$

The Darcy friction factor, *f*, is selected from a chart known as the Moody diagram. The Moody diagram, which is obtained from experiment, is a family of curves that relate the friction factor to Reynolds number, Re, and the relative roughness of the pipe, e/D.



The Reynolds number is

$$Re = \frac{\rho VD}{\mu} = \frac{VD}{\upsilon} = \frac{QD}{A\upsilon} = \frac{Q}{\left(\frac{\pi}{4}D^2\right)\frac{\upsilon}{D}} = \frac{4Q}{\pi D\nu}$$

We can calculate a convection heat transfer coefficient, h, in each pipe once we know the flow velocity using the Dittus-Boelter equation

$$\frac{hD}{k} = 0.023\left(\frac{V\rho D}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.4}$$

in which all material properties are evaluate at the bulk temperature

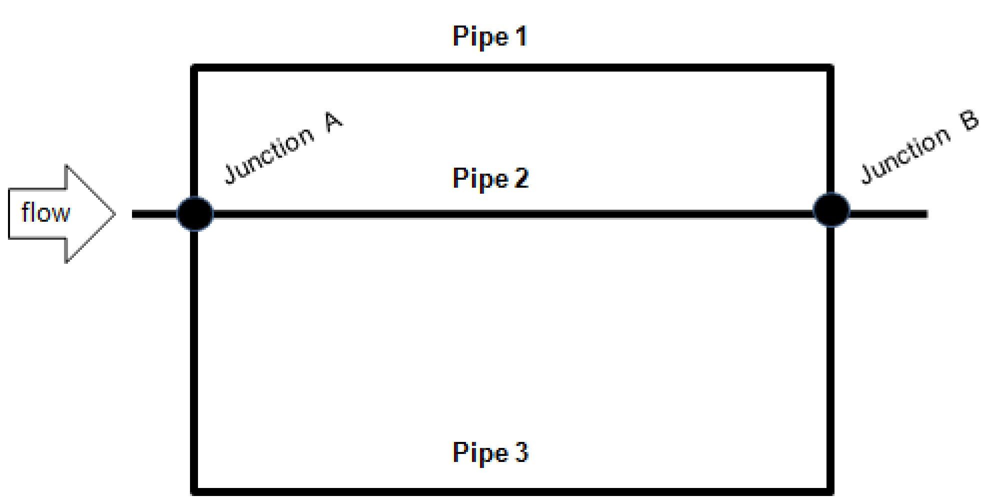
$$T_{bulk} = \frac{T_{wall} + T_{fluid}}{2}$$

Properties for water are:

T [C]	ρ [kg/m^3]	C_p [J/kg C]	μ [kg/m s]	k [W/m C]
20	998.	4182.	1.002e-03	0.603
40	992.	4179.	0.651e-03	0.632
60	983.	4185.	0.462e-03	0.653
80	972.	4197.	0.350e-03	0.670

Application

Water is flowing through the 3 pipes shown in the network below. Each horizontal pipe has a diameter of 0.15 m and a roughness ratio of e/D=0.0002. The pipe lengths are: L_1=50m, L_2=25m, and L_3=100m. The total volumetric flowrate is Q=0.1 m^3/sec. Determine the flow rate in each pipe.



The solution is an iterative process that starts off by guessing the volumetric flow rate in each pipe in order to calculate a Re number and friction factor. We can use the friction factor (f=0.015) from problem 1 as an initial guess because the 3 pipes in this problem are similar to the pipe in Problem 1 and the total flow rate is the same. The pressure drop (or, head loss) in each pipe measured between Junction A and Junction B must be the same. The calculation procedure starts off by calculating the head loss in each pipe, updating the flow rate, determining a new friction factor, and then recalculating the head loss. This iterative loop is continued until the head loss in each pipe is equal. This is easily done using a computer, Following is 1 iterative step.

Given:

- Q_T = 0.1 m^3/sec
- D = 0.15 m, A = 0.0181 m^2
- L_1 = 50 m, L_2 = 25 m, L_3 = 100 m

Calculate head loss in each pipe using f=0.015 from problem 1

$$h = f\frac{L_i}{D^5}\frac{8Q_i^2}{g\pi^2} = \left[\frac{8f}{gD^5\pi^2}\right]L_iQ_i^2 = \frac{8(0.015)}{(9.8)(0.15)^5\pi^2}L_iQ_i^2 = 16.3L_iQ_i^2$$

$$h = (16.3)(50)Q_1^2 = 817Q_1^2$$

$$h = (16.3)(25)Q_1^2 = 408Q_2^2$$

$$h = (16.3)(100)Q_1^2 = 1630Q_3^2$$

Calculate the flow rate in each pipe

$$Q_1 = \sqrt{\frac{h}{817}} = 0.0350\sqrt{h}$$

$$Q_2 = \sqrt{\frac{h}{408}} = 0.0495\sqrt{h}$$

$$Q_3 = \sqrt{\frac{h}{1630}} = 0.0248\sqrt{h}$$

$$Q_T = Q_1 + Q_2 + Q_3 = 0.109\sqrt{h}$$

We are also given that Q_T = 0.1. Therefore, the flow rate in each pipe can be calculated as follows:

$$\frac{Q_1}{Q_T}=\frac{0.0350\sqrt{h}}{0.109\sqrt{h}}=0.321$$	$Q_1=(0.321)(.1)=0.0321$
$$\frac{Q_2}{Q_T}=\frac{0.0495\sqrt{h}}{0.109\sqrt{h}}=0.454$$	$Q_2=(0.454)(.1)=0.0454$
$$\frac{Q_1}{Q_T}=\frac{0.0248\sqrt{h}}{0.109\sqrt{h}}=0.228$$	$Q_3=(0.228)(.1)=0.0228$

Calculate a new Reynolds number for each pipe, use the Moody diagram to obtain a friction factor, and then calculate the head loss.

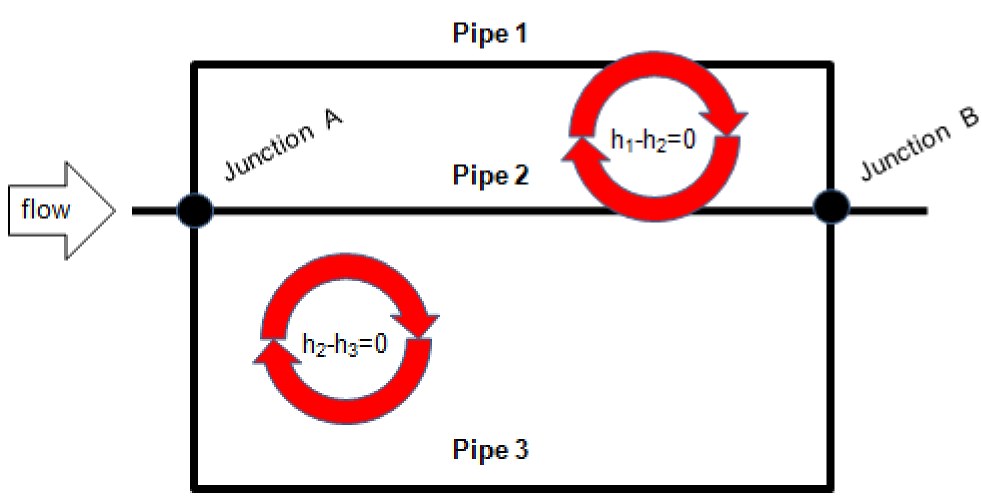
$Re_i=\frac{4Q_i}{\pi D\upsilon}$	f_i from Moody diagram	$h_i=f_i\frac{L_i}{D^5}\frac{8Q_i^2}{g\pi^2}$
$2.72*10^5$	0.0165	0.937
$3.85*10^5$	0.0160	0.898
$1.93*10^5$	0.0172	0.968

The head loss between 2 nodes in a pipe network must be the same. Comparison of h_1, h_2 and h_3 shows that an adjustment should be made to the flow rate in each pipe. However, we are probably close enough for a hand calculation due to our inability to interpolate an accurate value for the friction factor from the Moody diagram.

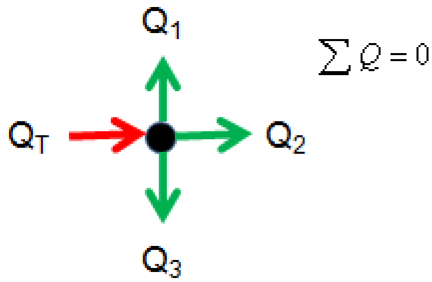
Computer Solution

We must rely on a computer solution to obtain a more accurate answer. There are several methods in the literature to form an iteration function [1,2]. The methods are based on

1. The algebraic sum of the pressure drop around each circuit must be zero.



2. Flow into each junction must equal flow out of the junction



3. The Darcy-Weisbach equation, or equivalent exponential friction formula, must be satisfied for each pipe (i.e., the proper relation between head loss and discharge must be maintained for each pipe).

$$\frac{1}{\sqrt{f}} = -0.86 ln\left[\frac{e/_D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right]$$

The above equation is the basis for the Moody diagram.

Network Analyzer
The LS-DYNA Pipe Flow Network Analyzer code should be considered as an alpha release. Our plans are to embed it in LS-PrePost with a GUI to draw the pipe network on the screen or read the CAD geometry. However, for now, the input is the old fashioned way of entering fixed format lines of data contained in a file with the name '**network.inp**'. The PC executable code is named **network.exe** and can be obtained from Shapiro@lstc.com.

The input file format is as follows with entries right justified:

Line 1 (5i10,a10) npipe, nnode, ndemand, ntank, nheight, units

Include npipe data cards (3I10, 4E10.0) nel, n1, n2, length, diameter, roughness, ftg_loss

Include ndemand data cards (I10, E10.0) node, Q

Include ntank data cards (I10, E10.0) node, elevation head

Include nheight data cards (I10, E10.0) node, elevation head

- npipe = number of pipes
- nnode = number of nodes
- ndemand = number of nodes with a specified flow rate. Positive for an inflow. There must be at least 1 demand node.
- ntank = number of nodes that represent an exit point. A tank represents an infinite reservoir to collect the exiting fluid. The elevation head is specified for the tank node. A

value of head=0 is acceptable, but it must be specified. There must be at least 1 tank in the network.

- nheight = number of nodes with a specified head.
- nel = pipe number
- n1,n2 = node numbers that span the pipe
- length = pipe length [m]
- diameter = pipe diameter [m]
- roughness = pipe roughness [m]
- ftg-loss = fitting loss in dimensions of equivalent length, L_e [m].
- elevation head = the node pressure specified as a total head [m]
- Q = volumetric flow rate [liter/min]

Pipe type	Roughness, e [mm]
Cast iron	0.25
Galvanized iron	0.15
Steel or wrought iron	0.046
Drawn tubing	0.0015

Fitting type	Equivalent length L_e/D
Globe valve	350
Gate valve	13
Check valve	30
90^o std. elbow	30
90^o long radius	20
90^o street elbow	50
45^o elbow	16
Tee flow through run	20
Tee flow through branch	60
Return bend	50

The input file

```
  3          2          1          1          0        SI                 → control
  1          1          2        50.        .15    .00003          0.     → pipe
  2          1          2        25.        .15    .00003          0.     → pipe
  3          1          2       100.        .15    .00003          0.     → pipe
  1      6000.                                                            → demand
  2         0.                                                            → tank
```

The output from network.exe

```
INPUT PHASE
  number of pipes                              =  3
  number of nodes                              =  2
  number of nodes with specified flow demands  =  1
  number of nodes specified as a tank          =  1
  number of nodes with specified elevations    =  0
  unit system SI or EN                         = SI
  pipe    n1    n2      length         dia   roughness    ftg-loss
     1     1     2  5.0000E+01  1.5000E-01  3.0000E-05  0.0000E+00
     2     1     2  2.5000E+01  1.5000E-01  3.0000E-05  0.0000E+00
     3     1     2  1.0000E+02  1.5000E-01  3.0000E-05  0.0000E+00
  node      demand
     1  6.0000E+03
  tank   elevation
     2  0.0000E+00

SOLUTION PHASE
   iteration=          1   error=  0.4698562
   iteration=          2   error=  9.0175442E-02
   iteration=          3   error=  5.4616481E-03
   iteration=          4   error=  3.0300583E-04
   iteration=          5   error=  1.6707927E-05

RESULTS
  pipe     m3/sec          lpm         lps         mps        fric          Re   hc [W/m2 C]
     1  3.1917E-02  1.9150E+03  3.1917E+01  1.8061E+00  1.6519E-02  2.6824E+05  4.4301E+03
     2  4.6034E-02  2.7620E+03  4.6034E+01  2.6050E+00  1.5882E-02  3.8689E+05  5.9383E+03
     3  2.2049E-02  1.3229E+03  2.2049E+01  1.2477E+00  1.7307E-02  1.8530E+05  3.2953E+03

  node   total head[m]  total head[Pa]      P-head[m]
     1      9.1582E-01      8.9546E+03     9.1582E-01
     2      0.0000E+00      0.0000E+00     0.0000E+00
```

References

1. V.L. Streeter, Fluid Mechanics, McGraw Hill Book Company, 6th ed., ISBN 0-07-062193-4, p565.
2. Fox & McDonald, Introduction to Fluid Mechanics,John Wiley and Sons, ISBN 0-471-27035-0