

Analysis of Flowrate in Loop Gas Pipeline Networks Using Pipe 2016 and Hardy Cross Method

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Abstract

Efficient and increased development of gaseous fuel as a complementary energy source requires a proper understanding of gas flow through pipeline networks and the required solution methods. This paper presents a comparative analysis of flowrate in loop gas pipeline systems using the Hardy Cross iterative method and Pipe 2016 (KYPIPE) computer program. A simple network model with four nodes, five pipe legs and two loops was manually analyzed based on the Hardy Cross procedure using Excel spreadsheet while comparing the effect of friction factors obtained from Moody's chart, Colebrook's implicit equation and Jain's explicit equation on the result obtained from the Hardy Cross method. The accuracy of the result was validated by running a single period flow analysis on Pipe 2016 with the same network. Upon completion, a one-way analysis of variance (ANOVA) test was used to compare the four results while a T-test was used to double-check the three results obtained from the various friction factors based on Hardy Cross individually against the software's result. Although, the mean plot showed that values obtained from Moody's Chart and Colebrook's equation compared more accurately with the software, the ANOVA and T-test set at 5% significant level shows that no statistically significant difference exist between the results; making all friction factors suitable for use in gas pipeline flow analysis.

Keywords: Gas pipeline networks, Hardy Cross method, KYPIPE, Pipe 2016, Flow analysis, Loop Pipe, Friction factor.

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INTRODUCTION

The world's ever increasing energy demand has made natural gas production and transmission a problem for all stakeholders. Being the cleanest form of energy, natural gas provides daily supply of energy required for both industrial and domestic use. Natural gas can be transported through Ships, Tanked cars (Railway), tanked trucks (Trucks) and Pipelines. The method adopted to move the gas depends on the nature of the gas, the volume of the gas, the destination/terrain and the frequency of demand [1]. However, pipeline has been described as the best means of gas transport. They are safer, cheaper and environmentally friendlier. According to STRATA, in America, transport by pipeline accounts for only 1.7% of annual fatalities to operators as opposed to 2.4% and 10% by rail and trucks respectively, also it cost about \$5 per barrel to transport oil and gas by pipeline compared to between \$10-\$20 per barrel for rail and trucks. The 2013 United State Energy Information Administration report also has it that majority of oil spills occur at the facility rather than in actual pipeline except when vandalized, these facilities are designed to contain spills quickly and as

such pipeline spills boast a high product recovery [2]. In view of the foregoing, a thorough understating of gas pipeline network topology and the required solution methods to the resulting non-linear equations is essential.

There are various methods used for analyzing pipeline network systems depending on the complexity of the network, the associated node connecting elements, the degree of accuracy and the level of convergence required. The Hardy Cross method is reputed as the oldest systematic method for solving pipeline network related problems before the availability of digital computers in the late 1960s [3], the method is an adaptation of the Moment distribution method, which was develop as a way to determine the moments in indeterminate structures but was later adapted to loop pipeline analysis. This method solves the loop equations by adjusting the flowrate to balance the energy equations [4], the results obtained per iteration are the correction of flow (ΔQ) rather than the flow (Q) obtained from using the loop-node method. Generally, there are four basic methods used to analyze

pipe networks, they are; the Hardy Cross method, the Node method, the Loop method and the Loop-node method. The node method is based on Kirchhoff first law (which states that the algebraic sum of the flows at any node is zero) while the loop method is based on Kirchhoff's second law (which state that the pressure drop around any closed loop is zero). The Loop-node method is a synergy of both the node and the loop method. The Hardy Cross method is widely preferred of the four methods because it is less sensitive to initial value prediction [5].

Today, various computer programs have been developed to analysis loop pipeline networks but most of these software are only suited for analysis of water flow in pipeline. KYPIPE (Pipe 2016) can be used to calculate steady state flows and pressures for any liquid and gas flow in pipeline systems. The program is written to accommodate any piping configuration, hydraulic components, fittings, flow meters and storage tanks [6]. It also allows flexibility of unit as computations can be carried out using both English and SI units. KYPIPE solution approach solves the full set of mass continuity and energy equations by utilizing efficient linearization schemes to handle the non-linear terms and a very powerful spare matrix routine developed by A.R. Curtis and J.K. Reid of the Theoretical Physics Division, UKAEA Research Group, Harwell, England. This approach accommodates elements such as closed lines, check valves, and regulating valves in a direct and very efficient manner, giving the best convergence characteristic when compared with other software [7].

Since the accuracy of a solution method in determining the resulting flowrate in pipeline is a function of the friction factor used, there is a need for comparison amongst the available equations to determine the optimum friction factor to use for such

calculations. The aim of this paper is to make a comparative analysis of flowrate using the Hardy Cross method and Pipe 2016. Also, this paper seeks to compare the effect of using three differently obtained friction factors (Moody's chart, Colebrook implicit equation and Jain's explicit equation) on the results obtain from the Hardy Cross method. For effective illustration of solution technique, the network is limited to a rectangular arrangement with four nodes, five pipe legs and two loops.

MATERIAL AND METHODS

MATERIALS

The materials used in this project are

- KYPIPE Software (PIPE 2016) [8]
- Microsoft Excel spreadsheet for manual computation of Hardy Cross.
- Fortran 95 compiler [9]

METHODS

KYPIPE software (PIPE 2016) and Hardy Cross method were used for the analysis. Short FORTRAN 95 programs were also written to execute and determine the friction factors based on the initial assumed flowrates for the Jain explicit equation and the Colebrook implicit equation used in the Hardy Cross. This was done particularly for the Colebrook implicit equation to allow the program run a series of iteration for the friction factor until the optimum value that satisfies the equation is determined. The moody friction factor was obtained from Moody's chart. A copy of the written FORTRAN 95 programs is attached to the appendix.

Method 1: solution approach to selected network using hardy cross method

The simple network chosen for analysis is given below;

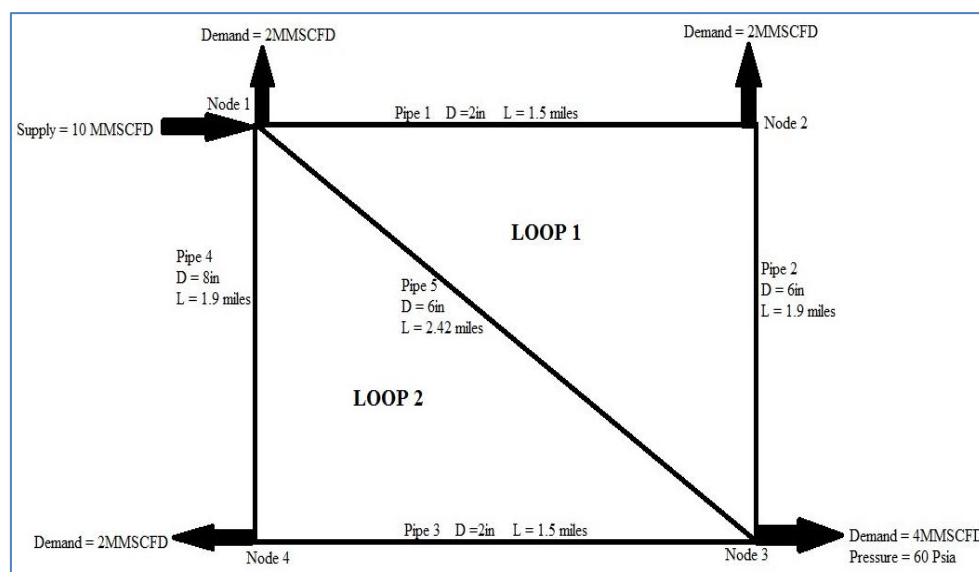


Fig-1: Selected Network

Given, Gas specific gravity = 0.67, Pipe roughness = 0.0006ft

Base Pressure = 14.7 Psia Base Temperature = 60⁰ F

Elevation changes are neglected

Where:

D = Diameter L = Length

Node: Junction Point, where fluid enters or leaves the networks

Loop: Closed path of interconnected pipes and nodes

Supply: Inflow into the network

Demand: Outflow from the network

Step 1: Making an initial guess of flow

An initial guess of possible flowrate and flow direction in pipe was made bearing in mind that the total inflow at each node must be equal to the total outflow at each junction.

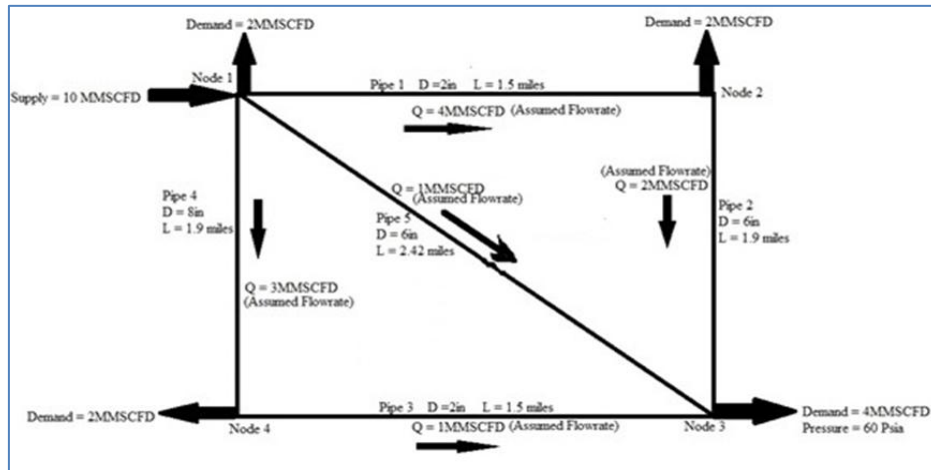


Fig-2: Assumed flow and direction

Step 2: Data Preparation

Unit Conversion

Although quantities in the Oil and Gas industry are measured in Field unit (English Unit), the Hardy Cross method uses S.I. unit and as such all

parameters including length, diameter and flowrate were converted to S.I. unit.

$$1\text{MMSCFD} = 0.32755\text{M}^3/\text{Sec}$$

$$1\text{ Miles} = 1609.344\text{ Meters}$$

$$1\text{ Inches} = 0.0254\text{ Meters}$$

Table-1: Conversion of Parameters

Pipe	Assumed Q (MMSCFD)	Q (M ³ /Sec)	L (Miles)	L (M)	D (in)	D (M)
Pipe 1	4.0000	1.3102	1.5000	2414	2.0000	0.0508
Pipe 2	2.0000	0.6551	1.9000	3058	6.0000	0.0205
Pipe 3	-1.0000	-0.3276	1.5000	2414	2.0000	0.0508
Pipe 4	-3.0000	-0.9827	1.9000	3058	8.0000	0.2032
Pipe 5	-1.0000	-0.3276	2.4200	3895	6.0000	0.1524

Determination of Friction Factor

The friction factor used was obtained from Moody's chart, Jain equation and Colebrook equation. Fortran 95 Programs were written to execute and determine the friction factor for Jain and Colebrook using their equations. The program is essential to allow Colebrook run a series of iteration for the friction factor until the optimum value that satisfies the equation is determined.

Jain explicit equation is give as

$$\frac{1}{\sqrt{F}} = 1.14 - 2\text{Log} \left(\frac{e}{D} + \frac{21.25}{N_{Re}^{0.9}} \right) \dots\dots\dots \text{Equation 1}$$

Colebrook Implicit equation is given as

$$\frac{1}{\sqrt{F}} = 1.74 - 2\text{Log} \left(\frac{2e}{D} + \frac{18.7}{N_{Re} \sqrt{F}} \right) \dots\dots\dots \text{Equation 2}$$

Where,

N_{Re} = Reynold's Number

F = Friction factor

e= Pipe roughness

D = Diameter

Determination of Flow resistance

The flow resistance is used to determine the effect of the various pipe properties on fluid flow (pressure losses). This depends on the hydraulic equation used; for this project, the Darcy-Weisbach equation was used. The head-loss and flow resistance are defined by equations 3 and 4 respectively.

$$H_f = r * Q * |Q| \dots\dots\dots \text{Equation 3}$$

$$r = \frac{32Fl}{g\pi^2 D^5} \dots\dots\dots \text{Equation 4}$$

Where, H_f = Head-loss Q = Flowrate

L = Length g = Acceleration due to gravity

π = 3.142 F = Friction factor

D = Diameter of pipe r = Flow resistance

Step 3: Determination of closed loop and head-loss

The two closed loops in the system were identified and clockwise direction of flow was assumed positive for head loss analysis (flow in the anticlockwise direction are assigned negative flowrate). Equation 3 was used to calculate the head-loss. It should be noted that the total sum of head-losses in a

loop should be equal to zero. The total head-loss was calculated by summing up the various calculated head-losses for each pipe within a loop.

$$\text{Total Head loss} = \sum hf = \sum_i^n (r * Q * |Q|) \dots\dots\dots \text{Equation 5}$$

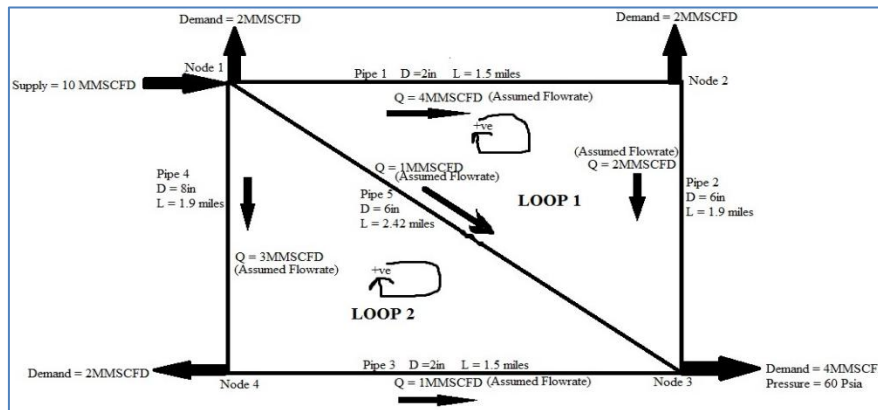


Fig-3: Identification of Closed loops

Step 4: Determination of the correction factor

Since an initial guess of flow was made for each pipe, balancing of head by the addition of a correction factor was done. This was done to achieve continuity of potential over the closed loop. The change in flow that will balance the head in the closed loop is given by:

$$\Delta Q = \frac{-1 * \sum (r * Q * |Q|)}{\sum (2 * r * |Q|)} = \frac{-1 * \sum_{i=1}^n Hf}{\sum_{i=1}^n (2 * r * |Q|)} \dots\dots\dots \text{Equation 6}$$

The calculated change in flow is added up to the assumed flow Q_0 for each pipe.

$$Q_1 = Q_0 + \Delta Q \dots\dots\dots \text{Equation 7}$$

Step 5: Correction for Joint Pipe

For pipes that are shared by two or more loops, the flow in the pipes must be balanced to satisfy the conditions in the two loops; this is generally done by using the calculated value (Q_1) for the pipe in the first loop as the Q_0 for the same pipe in the second loop. Depending on the flow direction, (-1) is used to multiply the Q_0 now computed as Q_1 to correct for direction change. The correction for flow and direction are repeated at every point the joint pipe appears for the two loops.

For instance, pipe 5 is shared between Loop 1 and 2, the assumed flow for pipe 5 and the direction assigned is used as its Q_0 and direction in Loop 1; the

head loss is calculated for this value and subsequently corrected based on the calculated ΔQ for loop 1. The corrected value Q_1 for Pipe 5 in Loop 1 is then used as Q_0 for Pipe 5 in Loop 2, since the direction of pipe 5 in loop 1 and 2 are opposite, (-1) is used to multiply the value thus Q_0 for pipe 5 in loop 2 become $-1 * Q_1$ (value obtained from pipe 5 in loop 1).

For the second iteration, the Q_1 for pipe 5 in loop 2 of the first iteration becomes the Q_0 for pipe 5 in loop 1 of the second iteration, change in direction is also corrected, therefore, Q_0 in loop 1 becomes $-1 * Q_1$ (value obtained from pipe 5 in loop 2 of iteration 1). This is done for every shared pipe across loops but for this network, only pipe 5 is shared. The iteration is repeated until $\Delta Q = 0$.

$$\text{If } \Delta Q = 0, \text{ then } Q_1 = Q_0.$$

Step 6: Repetition of process

Step 1-5 is repeated using values obtain for the other friction factors. The table below shows a model of the first iteration using values obtained from Moody's chart. The result obtained from the whole analysis for the three friction factor is presented in the result and discussion section of this paper.

Model for Hardy Cross Calculation

Table-2: Table Illustrating Hardy Cross using values obtained from Moody's chart

		Pipe	Q_0 (mmscfd)	Q_0 (m ³ /sec)	F	r	$H_f = rQ Q $	$2r Q $	$\Delta Q = \frac{-1 * \sum r * Q * Q }{2 * \sum r * Q }$	$Q_1 = Q_0 + \Delta Q$
		Pipe 1	4.0	1.3120	0.0276	6513873	111818720	170689544	-0.6534612	0.656738773
	Loop 1	Pipe 2	2.0	0.6551	0.0205	252219.1	108241.362	330457.523	-0.6534612	0.001638773
		Pipe 5	-1.0	-0.3276	0.0205	321253.6	-34477.503	210485.371	-0.6534612	-0.981061227
Iteration 1						$\sum_{i=1}^n x$	111892484	171230487		
	Loop 2	Pipe 3	-1.0	-0.3276	0.0276	6513873	-6990803.8	42678899.9	0.15512749	-0.172472508
		Pipe 4	-3.0	-0.9827	0.0191	55765.28	-53852.4894	109601.077	0.1551274	-0.827572508
		Pipe 5	2.9951495	0.981061227	0.0205	321253.6	309200.547	630338.94	0.1551274	1.136188719
						$\sum_{i=1}^n x$	-6735455.74	43418839.9		

METHOD 2: SOLUTION APPROACH TO SELECTED NETWORK USING KYPIPE (PIPE 2016)

KYPIPE was used to analyze the flow in the selected network below;

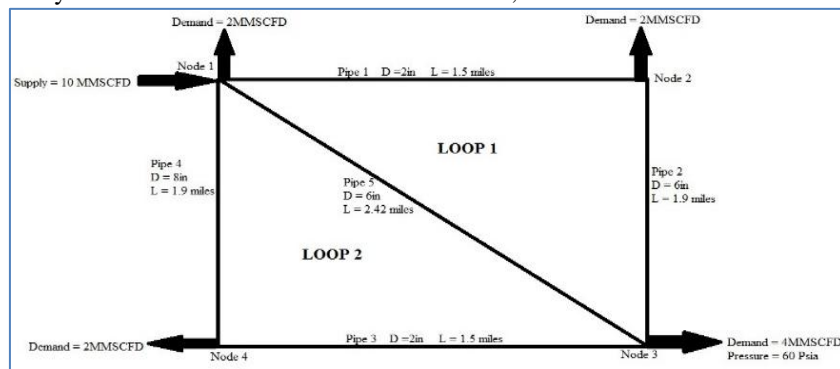


Fig-4: Selected Network

Step 1 - Initial Preparation

Initial steps include file selection, background preparation, and system data selections.

File Selection – Pipe 2016 was launched and a new data file was created.



Fig-5: New file specification on KYPIPE (Pipe 2016)

System Data Selection – It was used to specify system data such as Unit for flow rate, the default head loss equation (Hazen-Williams or Darcy-Welsbach's equation), the fluid property and other network and flow associated defaults. For this project, Darcy-

Welsbach head loss equation was used, also English unit was unit and the flowrate was in MSCFD as opposed to the MMSCFD in the network, so the values were multiplied by 1000 to accommodate for unit difference.

Fig-6: Gas Property Specification

Fig-7: Selecting of Gas for property determination

Background Preparation: This is generally used to import a drawing, map image, utilize grid lines or choose not to use a background. For area with well-defined aerial map, such map can be downloaded for

upload for proper layout definition. Skeletonized image of the network pipe distribution was drawn on the selected grid with specification of distance between points.

Fig-8: Grid Selection

Step 2 - System Layout

The system was laid out accordingly on the grid and relevant pipe specifications (including pipe length, diameter, roughness and material), node demand and supply were made.

Pipe Layout: Single Right click was used to add Junction node, while pipes were automatically laid between junctions.

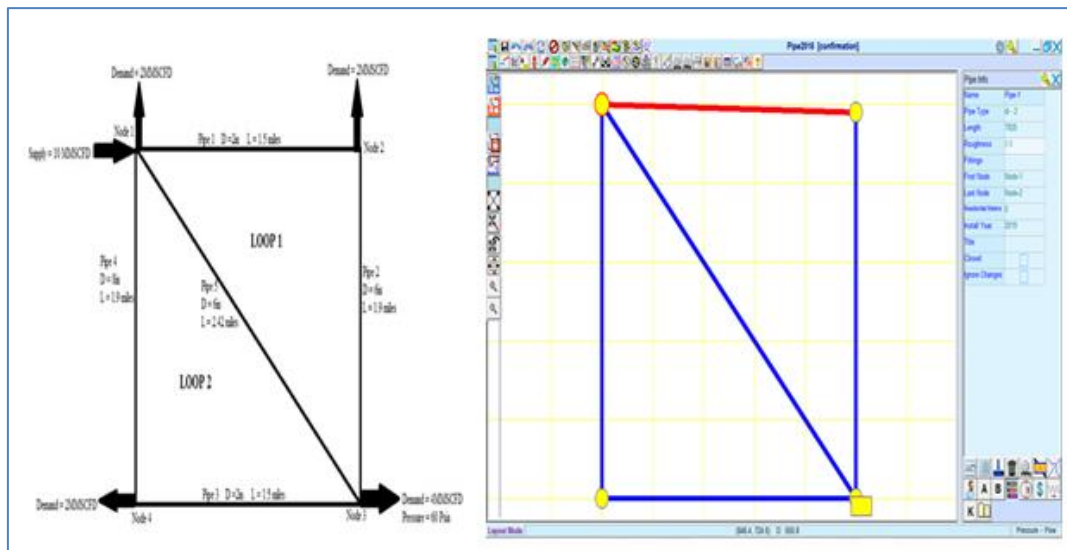


Fig-9: Pipe layout of structure

Pipe data specification: This was used to edit pipe properties for each pipe, each pipe was left click upon to edit its properties.

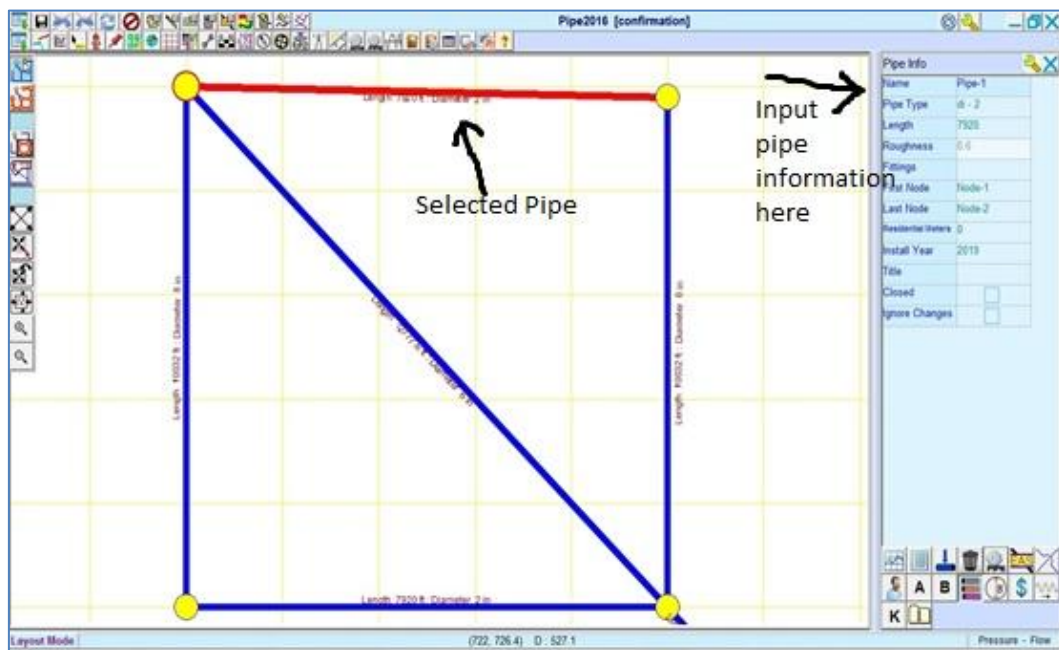


Fig-10: Pipe data specification

Node data specification: Node demand and supply were computed for each node, pressure was also

specified for fixed grade node(nodes where demand pressure required is specified).

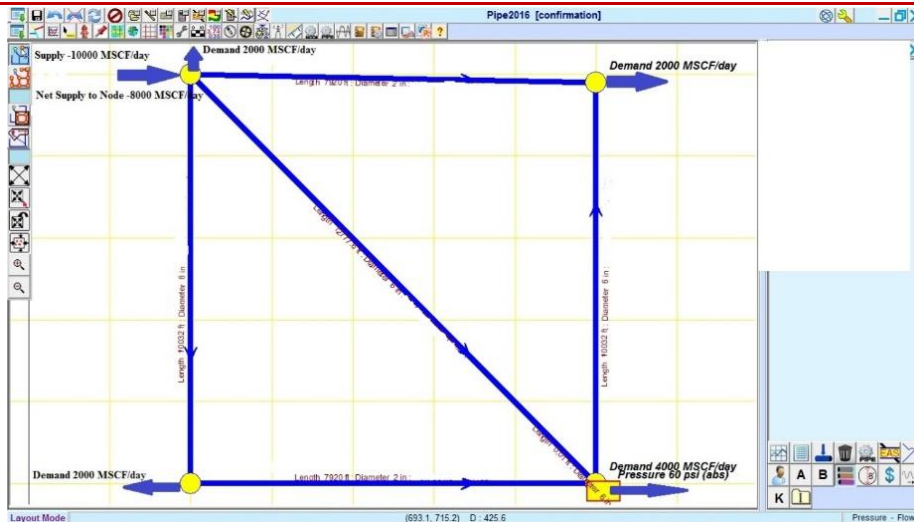


Fig-11: Nodal data specification

Step 3: Analyze System and Review Results

This was used to analyse the system for error check, unspecified parameters and complete flow analysis of the network.

Data Check and Run Analysis: Error Check was selected under the system analysis option to check for any error in network. If errors are flagged, necessary corrections should be made so that network can be analysed. If its message "No Errors", analysis can be completed.

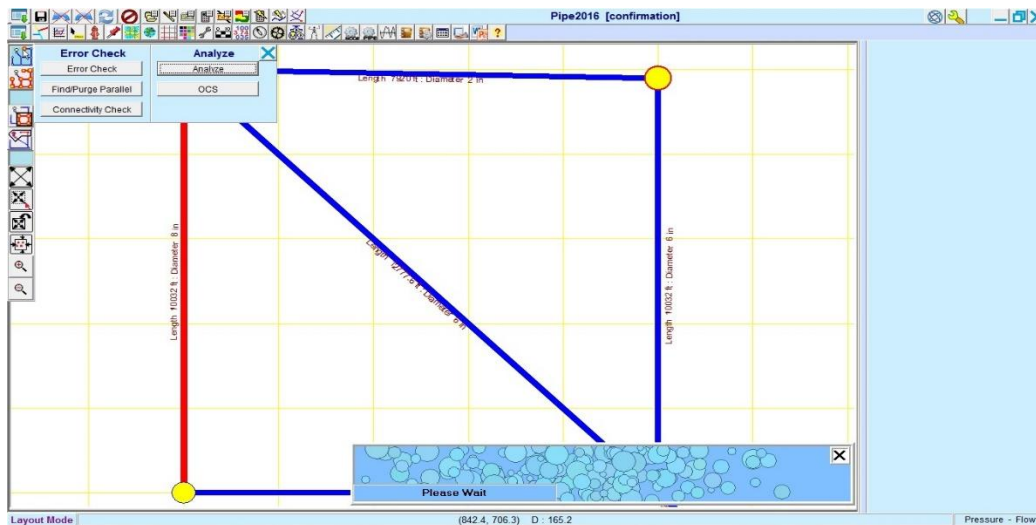


Fig-12 :Error check and analysis

Result Presentation: Results Obtained are presented in subsequent section

One-way analysis of variance (anova) test and t-test

A one-way analysis of variance test is a decision making tool used to determine the presence of statistically significant differences between the means of independent data set. It tests to validate the null hypothesis, H_0 ;

$$H_0 = \mu_1 = \mu_2 = \mu_3 = \mu_4 \dots = \mu_n \dots \text{equation 8}$$

Where, H_0 = Null Hypothesis μ_1 = Group mean
n = No of data set

If, however, the test returns a statistically significant result, we accept the alternative hypothesis, H_A ;

$$H_A = \mu \text{ is not equal}$$

On the other hand, a T-test is used to validate the null hypothesis for two data sample, this may be done for data sample of equal or unequal variance.

The ANOVA and T-test were done using the data section of the Microsoft excel spreadsheet as shown below; For ANOVA Test

Step 1: Choose the required analysis type on the data analysis section

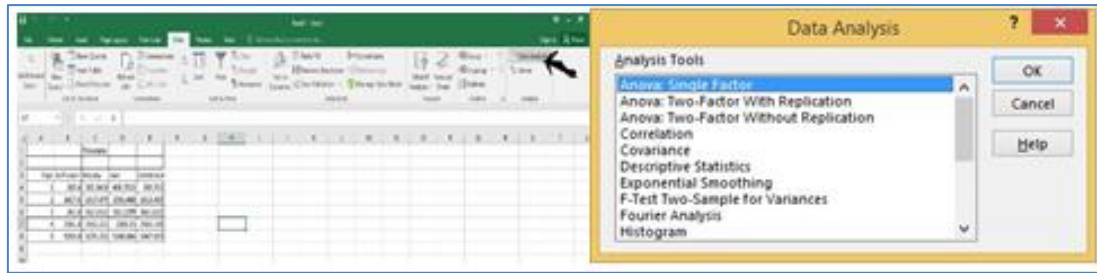


Fig-13: Data Section on Excel

Step 2: Compute the required data for analysis by selecting the column where data are assigned

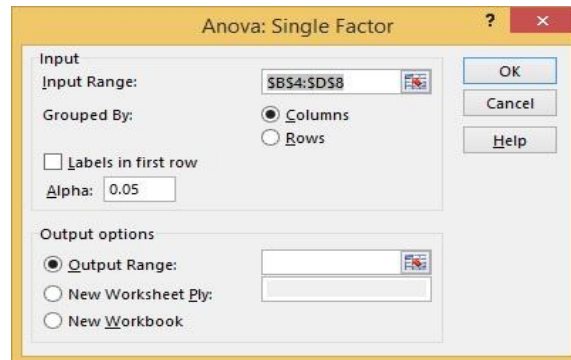


Fig-14: Computation of data

For T-Test

Step 1: F-test is first done to determine similarity of variance

Steps required are as previously itemized

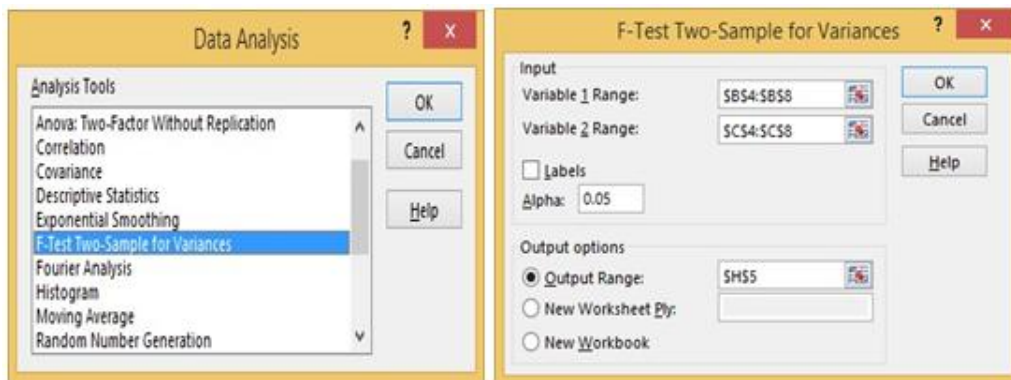


Fig-15: F-Test

Step 2: Since the variance are difference, the appropriate T-test option is selected and executed.

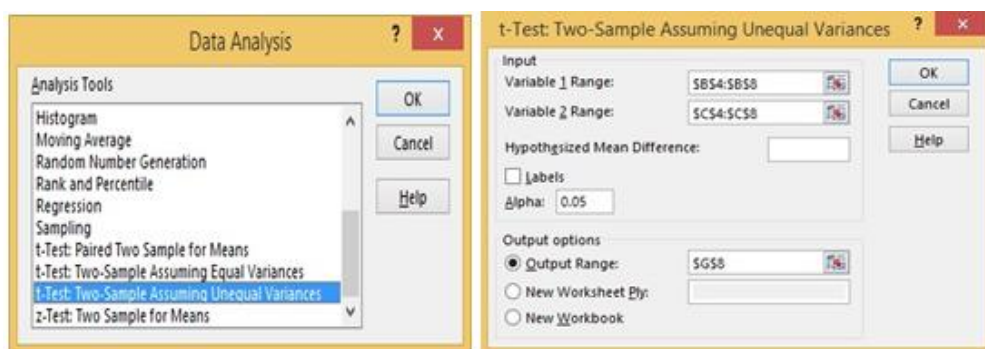


Fig-16: T-Test

RESULTS AND DISCUSSION

The result obtained from the various calculations are presented below

Flowrate Analysis

The value of the flowrate (mscfd) is presented in the table below

Table-3: Calculated Flowrate (mscfd)

Pipe	Software	Moody	Jain	Colebrook
1	382.4	382.5416423	408.352265	386.5509541
2	1617.6	1617.478658	1591.66803	1613.469346
3	361.8	362.532074	383.129889	366.1625472
4	2361.8	2362.552374	2383.15019	2366.182847
5	5255.8	5255.292484	5208.88405	5247.652699

Table 3 shows that all the flowrates obtained from the various friction factors compared reasonably with the software although values obtained from

Moody's Chart and Colebrook compared more accurately with the software.

ANOVA Test

Anova: Single Factor

Table-4: ANOVA Result

SUMMARY						
Groups	Count	Sum	Average	Variance		
Software	5	9979.4	1995.88	4044401.692		
Moody	5	9980.39723	1996.079446	4043022.963		
Jain	5	9975.18442	1995.036885	3939491.047		
Colebrook	5	9980.01839	1996.003679	4025826.667		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.491605528	3	1.163868509	2.90011E-07	1	3.238872
Within Groups	64210969.48	16	4013185.592			
Total	64210972.97	19				

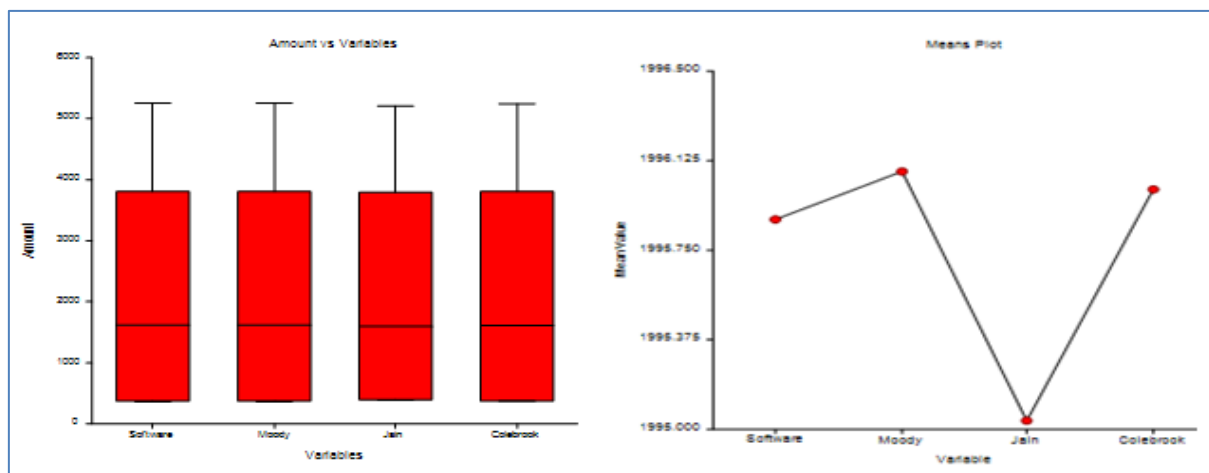


Fig-17: Box plot and mean plot from ANOVA

From Table 4; since $F < F_{crit}$ in the test, we accept the null hypothesis as defined in equation (8), that coupled with the box plot distribution shows that there are no statistically significant differences between

the four result. The mean plot however shows that values obtained from Moody's chart and Colebrook equation are closer to the Software's result thus establishing the observation from table 3.

T-Test

The T-Test is used to confirm the result obtained from the ANOVA test, since T-test can only be carried out on two data set, each of the friction factor outputs is compared to the software individually. Since

table 4 already shows the variance is different, the result of the F-test is not computed.

Software and Moody

T-Test: Two-Sample Assuming Unequal Variances

Table-5: Software and Moody's T-test

	<i>Software</i>	<i>Moody</i>
Mean	1995.88	1996.079446
Variance	4044401.692	4043022.963
Observations	5	5
Hypothesized Mean Difference	0	
df	8	
t Stat	-0.000156822	
P(T<=t) one-tail	0.499939357	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.999878714	
t Critical two-tail	2.306004135	

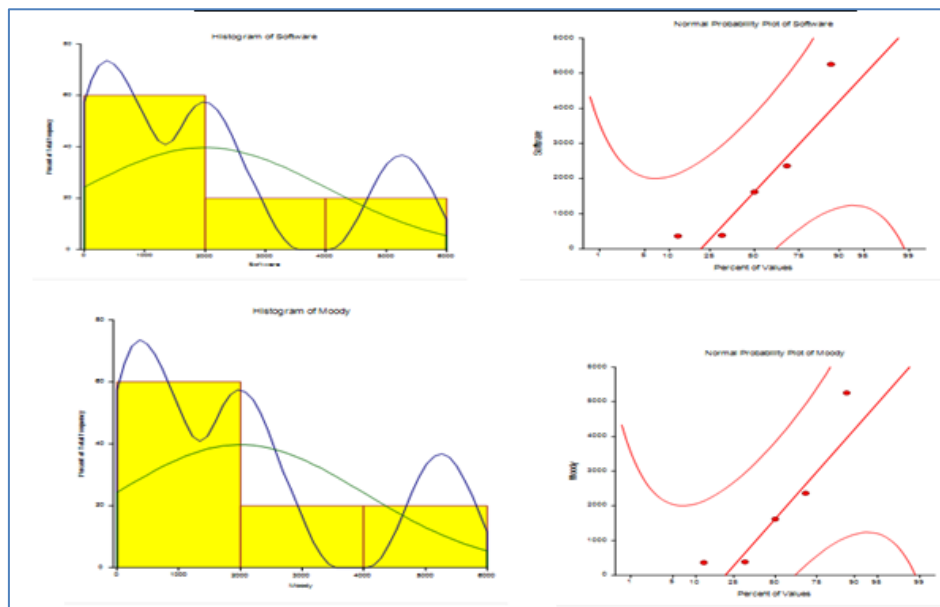


Fig-18: Histogram and Normal Probability distribution for Software and Moody

Since t Stat is less than t Critical on table 5, we accept the null hypothesis, also comparisons of the superimposed density and normal density curve on the histogram shows that the results are similar.

Software and Colebrook

T-Test: Two-Sample Assuming Unequal Variances

Table-6: Software and Colebrook's T-test

	<i>Software</i>	<i>Colebrook</i>
Mean	1995.88	1996.003679
Variance	4044401.692	4025826.667
Observations	5	5
Hypothesized Mean Difference	0	
df	8	
t Stat	-9.73502E-05	
P(T<=t) one-tail	0.499962355	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.99992471	
t Critical two-tail	2.306004135	

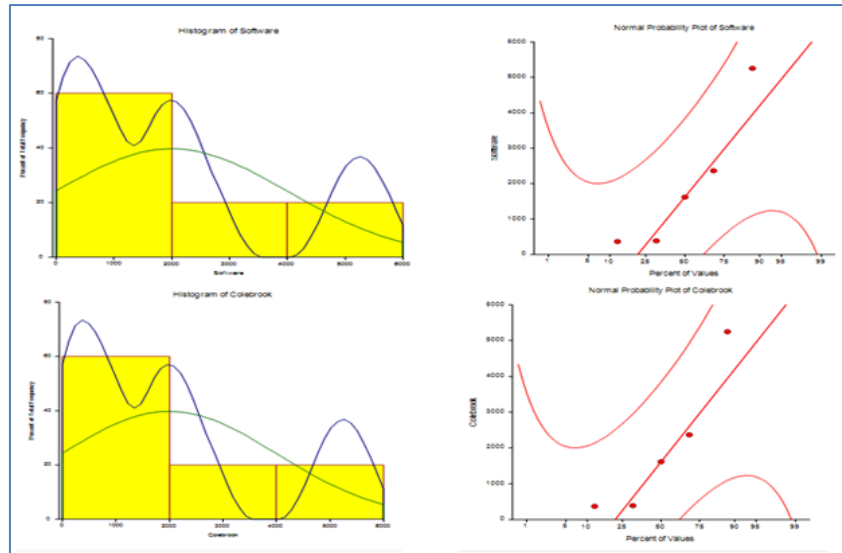


Fig-19: Histogram and Normal Probability distribution for Software and Colebrook

Data also establish the acceptance of the null hypothesis

Software and Jain

T-Test: Two-Sample Assuming Unequal Variances

Table-6: Software and Jain's T-test

	<i>Software</i>	<i>Jain</i>
Mean	1995.88	1995.036885
Variance	4044401.692	3939491.047
Observations	5	5
Hypothesized Mean Difference	0	
df	8	
t Stat	0.000667213	
P(T<=t) one-tail	0.499741989	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.999483979	
t Critical two-tail	2.306004135	

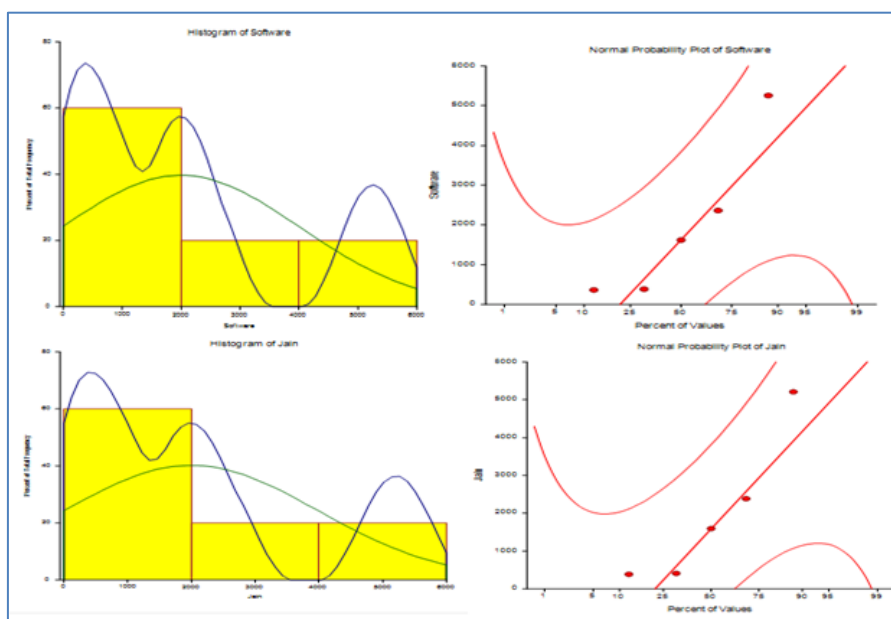


Fig-20: Histogram and Normal Probability distribution for Software and Jain

The box plot, superimposed density and normal density plot all show that there is no problem with the normality. Also the P-value from table 4 shows that the null hypothesis cannot be rejected. In essence there is no statistically significant difference between the four results. However, the mean plot shows that the values obtained from using the Moody's Chart and Colebrook equations are closer to the software's results.

CONCLUSION

The Hardy Cross method is a powerful manual flow analysis method that is capable of giving precise and accurate result comparable to sophisticated software irrespective of the complexity or simplicity of the network as shown in this research. Nevertheless, this research has also shown that its usage is sensitive to the choice of friction factor although the difference might not be statistically significant as shown by the ANOVA and T-test.

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APPENDIX

Program used for Colebrook

Program Colebrook

Implicit none

real::f, e, d, de, Re, ee, dm, G, q, N, B !N in cp, v in ft/sec, d in ft, de is density

!G is gas gravity, F is the initial fiction facor, Y is the answer from iteration

!B is colebrook friction factor, Re is the reynolds number

Integer:: Iteration

logical:: Y

Y=.True.

print*, 'Welcome to Colebrook Friction Factor Application'

Print*, "

print*, 'enter q in mcfd, q'

Print*, "

read*, q

print*, 'enter the diameter in inche, d'

Print*, "

read*, d

print*, 'enter the value of the viscosity in centipose, N'

Print*, "

read*, N

print*, 'enter the value of the specific gravity, G'

Print*, "

read*, G

de=G*0.07637

print*, 'The density of the gas is equal to', de

Print*, "

Re=(20*q*G)/(N*d)

print*, 'Reynolds number is equal to', Re

Print*, "

dm=d*0.0254

print*, 'enter corresponding roughness for pipe material, e'

Print*, "

read*, e

ee=e*0.305

Iteration=0

F=0.0056+0.5*Re**(-0.32)

print*, 'Value of f is', f

Print*, "

do while(Y)

B=(1/(1.74-

2*LOG10((2*(ee/dm))+(2.15/(Re*SQRT(f))))))**2

Print*, 'Friction factor is equal to', B


```

Print*, "
Print*, 'The result generated will be used for the next
iteration'
Print*, "
if (F==B)then
Y=.false.
else
F=B
Iteration=Iteration+1
Print*, 'Iteration', Iteration
Y=.True.
end if
end do
print*, 'The friction factor using Colebrook is given as',
F
print*, 'Thank you'
end program Colebrook

```

Program used for JAIN

```

program Jain
implicit none
real::f, e, d, Re, G, q, N, dm, ee !N in cp, v in ft/sec, d in
ft, dm is diameter in meter, ee is the roughness in meter,
G is gas gravity
print*, 'Welcome to Jain Friction Factor Application'
print*, "
print*, 'enter q in mcfd, q'
print*, "

```

```

read*, q
print*, 'enter the diameter in inche, d'
print*, "
read*, d
print*, 'enter the value of the viscosity, N'
print*, "
read*, N
print*, 'enter the value of the specific gravity, G'
print*, "
read*, G
print*, "
Re=(20*q*G)/(N*d)
print*, 'Reynolds number is equal to', Re
print*, "
dm=d*0.0254
print*, 'enter corresponding roughness for pipe material,
e'
print*, "
read*, e
ee=e*0.305
F=(1/(1.14-(2*LOG10((ee/dm)+(21.25/Re**0.9)))))**2
print*, 'Value of f is', f
print*, "
print*, 'The friction factor using Jain is given as', f
print*, "
print*, 'Thank you'
END PROGRAM JAIN

```