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OPTIMIZATION OF FRICTION FACTOR FOR AEROSPACE DUCT OF EQUIPMENT COOLING SYSTEM OF AIRCRAFT

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ABSTRACT

This paper discuss about the optimized friction factor for aerospace duct of Equipment cooling system of aircraft. Equipment Cooling is provided to maintain assigned temperature conditions in equipment compartment for satisfactory working of Line Replaceable units (LRUs) which are installed inside equipment compartment. Force air cooling is provided to these LRUs using Air Conditioning system (ACS) air. During up gradation programmes of aircraft due to introduction of new LRUs, there remains a requirement of redistribution of flow through complex duct geometries to meet their additional cooling requirements. In the present practice, designers carryout the redistribution of flow of air through these complex ducts using Continuity & Bernoulli's equation assuming approximate friction factors of head loss which can lead to improper results. In this paper first theoretical calculation for duct with new LRUs is carried out with present practice. After Theoretical calculation, complex duct geometry with calculated diameter is fabricated. The fabricated complex duct is installed on ECS test Rig in similar way as in Aircraft to maintain transient condition. The experimental mass flow rate for each section is measured & recorded. The Experimental calculation of roughness of all pipes in Complex duct geometry is carried out by Profilometer. By using Swamy Jain equation, the friction factor and mass flow rate is calculated. The percentage deviation in mass flow rate in Theoretical, Experimental are calculated by Swamy Jain Equation is compared and deviation is observed. Taking Experimental mass flow rate is main criteria the optimized friction factor formula is derived and mass flow rate based on optimized friction factor is calculated. This optimized friction factor mass flow rate is compared with experimental and very close results obtained i.e. the percentage deviation is very less. This research aims to determine the optimized friction factor through Aerospace ducts. Further, it has yielded optimized friction factor by carrying out theoretical *analysis correlated by experimental trials on ECS test rig. Optimized friction factor has helped in estimating the accurate head loss through ducts which has subsequently helped in designing the complex duct geometries.*

Keywords: Environmental Control System, Line replacable unit (LRUs), Flow analysis,Equipment Cooling System

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NOTATIONS

ρ = Density of air

μ = Dynamic Viscosity

ν = Kinematic Viscosity

m^* = Mass flow rate

m_{13}= air mass flow rate in branch 13

V = Initial Velocity of the air

f = Darcy friction factor

R_h = Hydraulic radius

D_h = Hydraulic Diameter

Re = Reynolds no of flow

$(h_f)_{01}$ = Head loss due To Friction in section 0 to1

$h_f)_{13}$ = Head loss due To Friction in section 1 to3

V_{01} = Mean velocity between section 0 & 1

V_{13} = Mean velocity between section 1 & 3.

E_0 = Energy at the section 0

E_1 = Energy at the section 1

E_3 = Energy at the section 3

P_0 = Pressure drop at section 0

P_1 = Pressure drop at section 1

P_3 = Pressure drop at section 3

D_{01} = Diameter of sections 0 to 1

D_{13} = Diameter of sections 1 to 3

A_{01} = Area of sections 0 to 1

A_{13} = Area of sections 1 to 3

L_{01} = Length of sections 0 to 1

L_{13} = Length of sections 1 to 3

ε = Surface roughness

1. INTRODUCTION

This research paper discusses about the optimisation of friction factor of Aerospace ducts to optimize duct designing of Equipment cooling system of a aircraft. Equipment Cooling is provided to maintain assigned temperature conditions in equipment compartment for satisfactory working of Line Replaceable units (LRUs) which are installed inside equipment compartment. Force air cooling is provided to these LRUs using Air Conditioning system (ACS) air. During up gradation programmes of aircraft due to introduction of new LRUs, there remains a requirement of redistribution of flow through complex duct geometries to meet their additional cooling requirements. In the present practice, designers carryout the redistribution of flow of air through these complex ducts using Continuity & Bernoulli's equation assuming approximate friction factors of head loss which can lead to improper results. It is also to be noted that to increase or decrease the speed of aircraft, pilots has to change the engine throttle rating. As engine rating changes, the bleed air pressure fed to Air Conditioning System LRUs varies. This leads to increment or decrement of turbo cooler turbine inlet pressure. Subsequently based on differential pressure across the turbine of turbo cooler the mass flow rate varies. The sudden variation of this engine rating leads to variation in flow through ducts and variation of pressure drop frequently due to variable Reynolds's no. Hence, there is a need to study the effects of variation of engine throttle on sudden increment and decrement of flow. Generally, it is very difficult for the designer's to predict the effect of variation of engine throttle on flow through complex duct geometries due to abrupt change in friction factor in transient condition. This research aims to determine the optimized friction factor through the Aerospace ducts. This research has yielded optimized friction factor by carrying out theoretical analysis correlated by experimental trials. Further, optimized friction factor has helped in estimating the accurate head loss through ducts which has subsequently helped in designing the complex Aerospace duct geometries.

2. LITERATURE REVIEW

To start a research project, it is very important to know the current methodologies used in industry and explore simple and accurate methodologies for analysis. The first step for flow analysis through these complex ducts using Continuity & Bernoulli's equation. Initial velocity of air to be found out for given diameter of pipe by continuity equation. The redistribution of flow carried out by Bernoulli's equation for which Reynolds number to be found out. The head loss is important factor for redistribution of flow. Total head loss in Pipe flow is calculated by Darcy-Weisbach formula $\mathbf{h_f = \frac{fLV^2}{2gD}}$

For head loss friction factor to be calculated, the Darcy friction factor formulae are equations based on experimental data and theory. Darcy-Weisbach friction factor, resistance coefficient or simply —friction factor and is four times larger than the Fanning friction factor [1]. For laminar flow, The Darcy friction factor for laminar flow in a circular pipe (Reynolds number less than 2320) is given by the formula: $f = \frac{64}{Re}$ Transition flow (neither fully laminar nor fully turbulent) flow occurs in the range of Reynolds numbers between 2300 and 4000. The value of the Turbulent flow in smooth conduits: The Blasius correlation is the simplest equation for computing the Darcy friction factor. Turbulent flow in rough conduits: The Darcy friction factor for fully turbulent flow (Reynolds number greater than 4000) in rough conduits is given by the Colebrook equation.

Colebrook–White equation: Colebrook–White equation (or Colebrook equation) expresses the Darcy friction factor(f) as a function of Reynolds number Re and pipe relative roughness ε / D_h, fitting the data of experimental studies of turbulent flow in smooth and rough pipes.[2][3] The equation can be used to (iteratively) solve for the Darcy–Weisbach friction factor f. For a conduit flowing completely full of fluid at Reynolds numbers greater than 4000, it is expressed as:

$$\frac{1}{\sqrt{f}} = -2*\log_{10}*\left(\frac{\varepsilon}{3.7Dh} + \frac{2.51}{Re\sqrt{f}}\right)$$

Some sources use a constant of 3.71 in the denominator for the roughness term in the first equation above.[4] Recently, the Lambert W function has been employed to obtain explicit reformulation of the Colebrook equation.[5] Colebrook equation can be solved by iteration using the Newton–Raphson method. Approximation of Cole brook equation is provided by Halland eqaution, Swamee Jain Equation, Serghides's solution and Goudar–Sonnad equation. The Haaland equation was proposed by Norwegian Institute of Technology professor Haaland in 1984. The Haaland equation is defined as: $\frac{1}{\sqrt{f}} = -1.8 * \log_{10} [\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}})]^{-2}$.

The Swamee–Jain equation[6] is used to solve directly for the Darcy–Weisbach friction factor f for a full-flowing circular pipe. It is an approximation of the implicit Colebrook–White equation. Swamee Jain equation is given by $f = 0.25 [\log_{10} ((\frac{\varepsilon}{3.7D}) + (\frac{5.74}{Re^{0.9}}))]^{-2}$. Goudar equation [8] is the most accurate approximation to solve directly for the Darcy–Weisbach friction factor for a full-flowing circular pipe. It is an approximation of the implicit Colebrook–White equation. Brkić shows one approximation of the Colebrook equation based on the Lambert W-function[9].Early approximations by Paul Richard Heinrich Blasius in terms of the Moody friction factor[10] $f = 0.316Re^{0.25}$. Johann Nikuradse in 1932 proposed that this corresponds to a power law correlation for the fluid velocity profile. Mishra and Gupta in 1979 proposed a correction for curved or helically coiled tubes, taking into account the equivalent curve radius. From literature survey it is concluded that Swamee Jain equation is latest refined available equation considering all the relevant factors. Hence Swamee Jain equation was selected for our application.

Detailed flow analysis regarding distribution of air through various LRUs of aircraft is carried out with the help of Continuity & Bernoulli's equation, to ensure appropriate flow distribution in respective LRUs. Head losses due to friction & bends during flow were calculated using friction factor $f = 0.0032 + \frac{0.210}{Re^{0.257}}$.

A sample theoretical calculation based on available mass flow rate is shown below:

Air mass Flow Rate outlet of turbo cooler = **400kg/hr**

Mass flow rate of cooling air supplied to Compartment 5 = 18 kg/hr

Mass flow rate of cooling air supplied to newly introduced LRUs = 400-18 = 382 Kg/hr

Absolute outlet Pressure from Turbo cooler = **1.2 kgf/cm^2**

Temperature of the air outlet from turbo cooler ≈ **15^0 C**

Properties of air at initial temperature are taken from thermodynamic table.

Density of air ρ **= 1.2kg/m^3**

Dynamic Viscosity μ = **1.81 x 10^{-5} N-s/m^2**

Kinematic Viscosity **ν = 1.51 x 10^{-5} m^2/sec**

Mass flow rate m* = ρ*A*V (Applying Continuity Equation)

$382/3600 = 1.2 * \frac{\Pi}{4} * D^2 * V$

Taking the initial Diameter of the pipe as 36mm= 0.036m

Initial Velocity of the air **V = 86.91 m/s**

Assuming the no pressure drop through pipelines during the flow due to less pressure gradient across turbo cooler outlet & newly introduced LRUs. The flow is assumed to be due to dynamic pressure gradient (i.e kinetic head gradient).

For find the head loss across the pipe lines we will calculate the friction Factor '**f**'

To calculate f, it is required calculate Reynolds no of flow:

$Re = \rho * D * V / \mu$

$Re = 1.2*0.036*86.91/1.81* 10^{-5}$

Re = 207431.6

As Re> 4000, the flow is Turbulent.

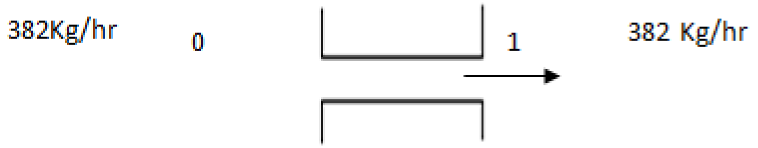
For $\mathbf{10^5 < Re < 4 \times 10^7}$ using the empirical relation for friction factor f

$f = 0.0032 + 0.210/ Re^{0.257}$

$f = 0.0032 + 0.210/ (207431.6)^{0.257}$

$f = 0.01223$

2.1. Calculations For Section 0 To 1



Energy balance equation between section 0 and 1

$E_0 = E_1 + (h_f)_{01}$

Using Bernoulli's equation between section 0 & 1

$$\frac{P_0}{\rho g}+\frac{V_0^2}{2g}+ Z_0 = \frac{P_1}{\rho g}+\frac{V_1^2}{2g}+ Z_1 + \textbf{head Losses}$$

Due to less pressure gradient across turbo cooler outlet & New LRUs.

It is assumed that pressure drop between sections 0 to 1 is negligible. Thus

$$\frac{P_0}{\rho g} = \frac{P_1}{\rho g}, \ \& \ Z_0 = Z_1$$

$L_{01} = 0.085$ m, $D_{01} = 0.036$m, $V_{01} = 86.91$ m/s

$\mathbf{V_{01}}$**:** mean velocity between section 0 & 1.

$$\frac{V_0^2}{2g} - \textbf{head Losses} = \frac{V_1^2}{2g} = \mathbf{E_1}$$

Head loss due To Friction in section 0 to1,

$$(h_f)_{01} = f * L_{01} * V^2_{01} / 2gD_{01} \quad {}_n$$

$$(h_f)_{01} = 0.01223*0.085*86.91^2 / 2*9.81*0.36$$

$$(h_f)_{01} = 1.112 \text{ m of air}$$

Velocity Head Available at the inlet = $V^2_{01} / 2g = 86.91^2 / 2 * 9.81 =$ **384.98**

Hence Energy at the section 1

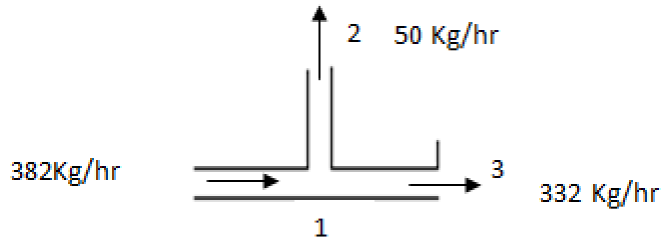
$$E_1 = E_0 - (h_f)_{01}$$

$$E_1 = 384.98 - 1.112$$

$$E_1 = 383.868 \text{ m of Air}$$

2.2. Calculations For Section 1 To 3,

Unit 1 & Unit 2 require 20 Kg/hr of cooling air at 15°C but due to availability of additional cooling air we are designing the system to supply cooling air to 25 Kg/hr each (Total 50 Kg/hr) in Branch 1-2



Energy balance equation between sections 1 & 3

$$E_1 = E_3 + (h_f)_{13}$$

Using Bernoulli's equation between section 1 & 3

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + Z_3 + \textbf{head Losses}$$

Assuming pressure drop between sections 1 to 3 is negligible & datum's are same

$$\frac{P_1}{\rho g} = \frac{P_3}{\rho g}\ , \ \& \ Z_1 = Z_3$$

V_{13}: mean velocity between section 1 & 3.

$$E_1 = V^2_{13}/2g + f*L_{13}*V^2_{13}/2g\ D_{13}$$

$$383.868 = (V_{13})^2/2g + f*L_{13}*V_{13}^2/2gD_{13}$$

$$383.868 = (V_{13})^2/2g\ [1 + f*L_{13}/D_{13}]$$

For calculating D_{13} in terms of V_{13} we are using continuity equation

2.2.1. By Continuity Equation

Required air mass flow rate in branch 13 $m_{13} = 332$ Kg/hr

$$m_{13}* = \rho*A_{13}*V_{13}$$

$$332/3600 = 1.2*\prod/4*V_{13}*D_{13}^{\ 2}$$

$$D_{13} = [332 * 4/(3600*1.2*\prod*V_{13})]^{\ 1/2}$$

$$D_{13} = 0.09785/\sqrt{}V_{13}$$

$$383.868 = V_{13}^2/2g\ [1 + 0.01223*0.305\sqrt{}V_{13}/0.09785]$$

$$V_{13}^{\ 2} + 0.03812(V_{13})^{5/2} - 7523.81 = 0$$

V_{13}=75.1697m/s & corresponding diameter will be

$$D_{13} = 0.3128/\sqrt{}75.1697$$

$$D_{13} = 36.08\text{mm}$$

So total friction loss due to flow between sections 1 to 3,

$$(h_f)_{13} = f*L_{13}*V^2_{13}/2gD_{13}$$

$$= 0.01223*0.305*75.1697^2/2*9.81*0.03608$$

$$= 29.77 \text{ m of air}$$

$$E_3 = 383.868 - 29.77$$

$$E_3 = 354.093 \text{ m of air}$$

So diameter of sections 1 to 3, $\Rightarrow D_{13} = 36$ mm,

In a similar manner calculations for remaining sections have been undertaken and results are tabulated at **Table-1**.

Table 1 Calculated diameters of pipelines at respective section supplying ECS air to LRUs

Section	**Mass flow rate Kg/hr**	**Length of pipe (m)**	**Energy at the inlet of section (E_{inlet}) m of air**	**Frictional Loss m of air**	**Energy at outlet of section (E_1) = E_{inlet}- FL**	**Iterative velocity V (m/s)**	**Calculated Diameter (mm)**	**Fabricated pipe (mm)**
0-1	382	0.085	385.4	1.112	383	86.91	35.9	36
1 to 3	332	0.305	383	37.98	345.01	82.2	34.5	36
1 to 2	50	0.385	383	97.59	285.4	74.8	14.03	14
2 to A	25	0.23	285.40	60.98	224.42	66.3	10.54	12
2 to B	25	0.062	285.40	20.27	265.13	72.1	10.10	12
3 to 4	291.8	0.175	345.01	20.60	324.40	79.7	34.5	34
3 to C	40.2	0.41	345.01	76.42	268.58	58.8	14.19	16
4 to 5	266.8	0.46	324.4	47.12	277.28	72.6	32.9	32
4 to D	25	0.375	324.4	67.30	257.09	56.6	11.41	12
5 to 6	232	0.14	277.3	14.33	262.94	70.6	31.12	32
6 to E	55	0.195	262.9	21.69	241.25	54.71	17.21	18
6 to F	177	0.4	262.9	24.42	238.52	54.4	30.97	32
5 to 7	34.8	0.46	277.2	81.92	195.35	60.3	13.04	12
7 to G	17	0.32	195.3	36.50	158.85	43.7	10.7	12
7 to H	17	1.045	195.3	99.19	96.16	40.6	11.1	12

3. EXPERIMENTALLY DETERMINATION OF VELOCITY OF AIR FLOW AT DISCRETE AIR OUTLET POINTS OF AIR CONDITIONING SYSTEM AND MASS FLOW RATE OF COOLED AIR SUPPLIED TO AVIONICS LRUS

Velocity of Air flow at discrete air outlet points of Air Conditioning System i.e Inlet to LRUs has been experimentally determined by designing an Environmental Control System (ECS) test rig as described below:

3.1. Experimental setup of ECS test rig

Aerospace ducts based on theoretical calculations mentioned at **Table 2** have been manufactured. These ducts were made of Aluminum alloy. An experimental Environmental Control System (ECS) test rig has been designed to simulate the actual layout of installation of Aerospace ducts into aircraft shown at **Figure-2.**

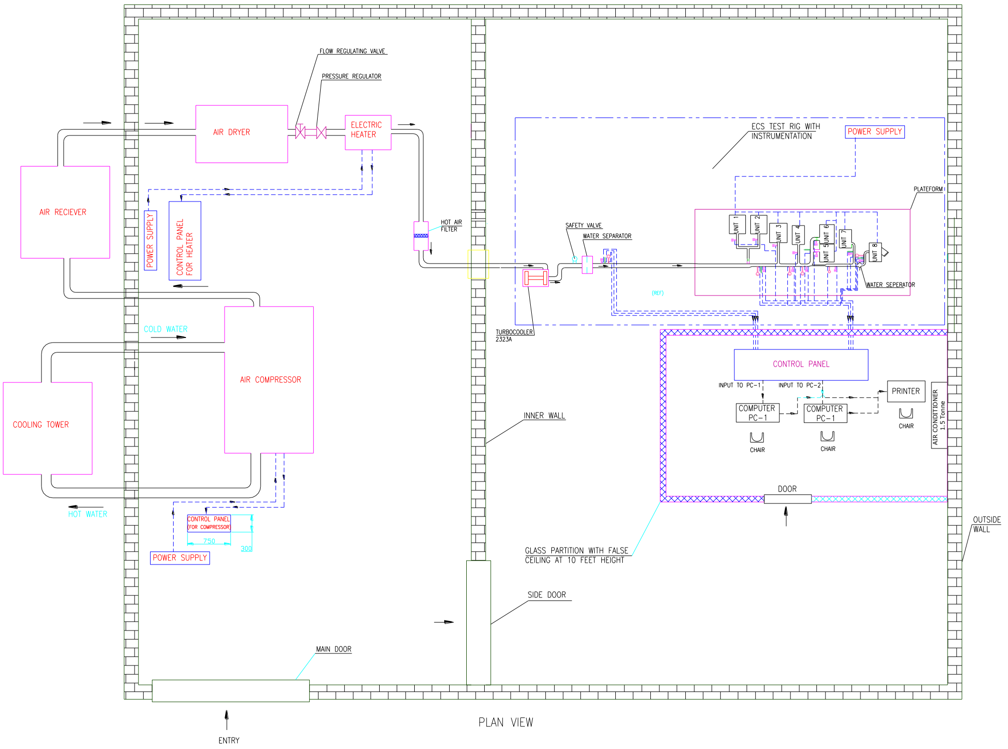


Figure1 ECS Test rig Layout

Aircraft turbo cooler is used on ECS test rig to simulate the system parameters based on variable input pressure and temperature. Thermal flow meters were installed at the duct to measure the Air flow rate supplied to particular LRU. To record and online recording of test rig parameters, PLC based control system has been designed. Physical components of ECS test rig are shown at **Figure 2**. Placement of thermal flow meters at the inlet of respective LRUs is shown at **Figure 3.**

Figure 2 Components of ECS test rig

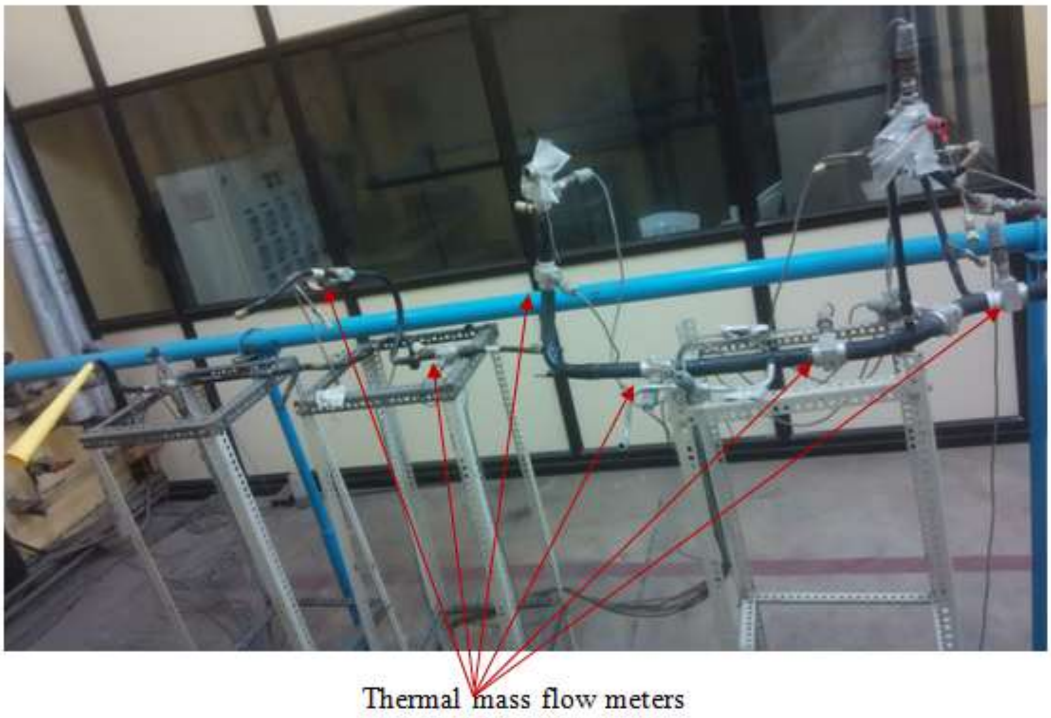


Figure 3 Installation of flow meter at the inlet of ECS ducts connected to respective LRUs

4. EXPERIMENTALLY DETERMINATION OF AVERAGE INTERNAL ROUGHNESS OF DUCTS THROUGH WHICH AIR IS SUPPLIED TO VARIOUS ACS DUCTS CONNECTED TO LRUS TO MEASURE THE AVERAGE ROUGHNESS OF AEROSPACE DUCTS, THE SAMPLE OF DUCTS OF INTERNAL DIAMETER ϕ34, ϕ28, ϕ18,ϕ16,ϕ14,ϕ12,ϕ10 HAVE BEEN TAKEN AND CUT INTO SEMICIRCULAR HALF. TO SECURE THE AEROSPACE DUCTS, A V GROVE FIXTURE WAS FABRICATED AND INTERNAL ROUGHNESS HAS BEEN MEASURED USING PROFILOMETER AS SHOWN AT FIGURE-4

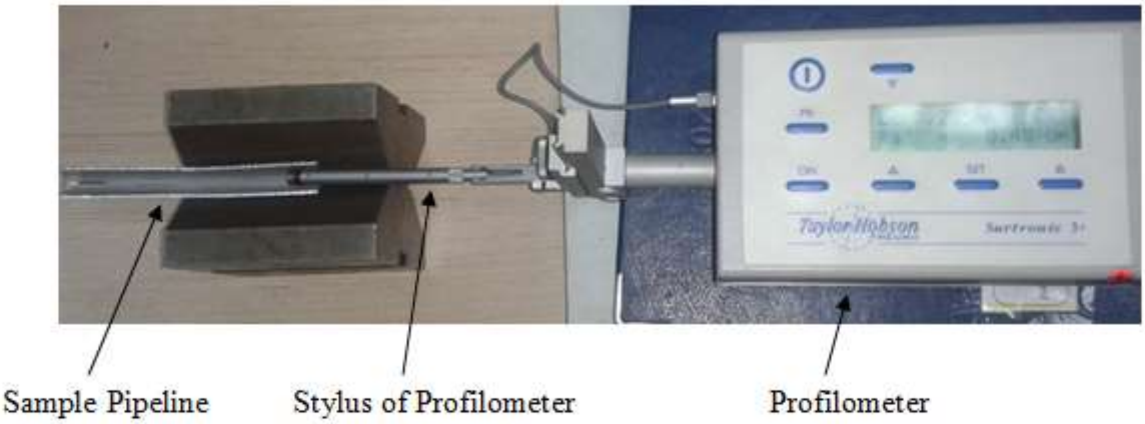


Figure 4 Measurement of surface roughness using Profilometer

Measured Value of ECS ducts of internal diameter ϕ34, ϕ28, ϕ18, ϕ16, ϕ14, ϕ12 and ϕ10 are tabulated at **Table-2.**

Table 2 Pipe samples with their surface roughness value

Aerospace ECS duct ∅34 cut Sample	**Internal Diameter (mm)**	**Average Roughness(μm)**
	∅34	0.24
	∅14	0.29
	∅10	0.315
	∅12	0.285
	∅18	0.345
	∅16	0.30
	∅28	0.30
	∅36	0.36

5. APPLICATION OF SWAMY-JAIN EQUATION TO CALCULATE FRICTION FACTOR OF AEROSPACE DUCTS USING EXPERIMENTALLY MEASURED AVERAGE FRICTION FACTOR & AVERAGE ROUGHNESS OF AEROSPACE DUCTS.

Based on the Swamy-Jain friction factor equation i.e.

$$f=0.25\ [\ \log_{10}(\ (\varepsilon/3.7D)+(5.74/Re^{0.9}))]^{-2}$$

Swamy-Jain friction factor for various sections is calculated as below:

To find the head loss across the pipe lines we have to calculate the friction Factor ‘**f**’

To calculate **f**, it is required to calculate Reynolds number of flow:

$$Re = \rho * D * V / \mu$$

$$\mathbf{Re} = 1.2*0.036*86.91/1.81*10^{-5}$$

$$\mathbf{Re} = 207431.6$$

As Re> 4000, the flow is Turbulent.

For $\mathbf{10^5 < Re < 4 \times 10^7}$ using the Swamy-Jain equation for friction factor f

$$f=0.25*\{\log[((\varepsilon_{01}*(V_{01})^{0.5})/3.7*1.0303*m^{0.5})+(5.74*\mu*V_{01}^{0.5}/\rho*V_{01}*1.0303*m_{01}^{0.5})]\}^{-2}$$

$$f = 0.03835$$

Based on above calculation, Swamy-Jain friction factor is calculated for different sections. Calculated Value of Swamy-Jain friction factor of ECS ducts are tabulated at **Table-3.**

Table 3 Calculated Swamy Jain friction factor at various sections

Section	Theoritical estimated mass flow rate Kg/hr	Length of pipe (m)	Rougness, µ	Fabricated pipe dia (mm)	Reynold's Number	Corrected Velocity, m/s	Swamy Jain Friction Factor
0-1	382	0.085	0.00036	36	207431.60	86.91	0.038346
1 to 3	332	0.305	0.00036	36	179817.01	75.34	0.038406
1 to 2	50	0.385	0.00029	14	68425.39	73.720	0.050157
2 to A	25	0.23	0.00029	14	38556.46	41.54	0.050729
2 to B	25	0.062	0.00029	14	37703.78	40.62	0.050757
3 to 4	317	0.175	0.00024	34	167843.46	74.45	0.034439
3 to C	40.2	0.41	0.0003	16	50097.16	47.22	0.048638
4 to 5	266.8	0.46	0.00024	32	163121.25	76.88	0.03510
4 to D	25	0.375	0.000315	10	50830.29	76.66	0.05930
5 to 6	232	0.14	0.00024	32	141432.84	66.66	0.035185
6 to E	55	0.195	0.000345	18	59193.39	49.60	0.048863
6 to F	177	0.4	0.00024	32	109663.91	51.69	0.035365
5 to 7	34.8	0.46	0.000285	12	55391.98	69.62	0.052987
7 to G	17	0.32	0.0003	16	21798.89	20.55	0.0499191
7 to H	17	1.045	0.0003	16	21993.87	20.73	0.049900

6. CALCULATION OF MASS FLOW RATE OF AIR SUPPLIED TO VARIOUS LRUS USING SWAMEE-JAIN FRICTION FACTOR:

After calculating, Swamy-Jain friction factor mentioned in Para-7, air mass flow rate supplied to various LRUs has been undertaken and details of sample calculation is placed below:

$$\text{Mass flow rate to Unit-1} = \rho * A_{4D} * V_{4D}$$

$$= 1.2 * \prod/4 * (0.036)^2 * 86.91$$

$$= 0.106156 \text{ kg/s}$$

$$= 382.16 \text{ kg/hr} \approx \mathbf{382\ kg/hr}$$

Based on above calculation, using Swamy-Jain friction factor revised mass flow rate is calculated for different sections and tabulated at **Table-4**.

Table 4 Revised mass flow rate based on Swamy Jain friction factor

Section	Velocity m/s	D=Inner Dia of pipe(m)	Density of Air	Mass flow rate (kg/s)	Revised Mass flow rate based on Swamy Jain equation (kg/hr)
0-1	86.91	0.036	1.2	0.106102509	381.969
1 TO 3	75.34	0.036	1.2	0.091977483	331.1189
1 TO 2	73.720	0.014	1.2	0.013611111	49
2 TO A	41.54	0.014	1.2	0.007669613	27.61061
2 TO B	40.62	0.014	1.2	0.009384845	27
3 TO 4	74.45	0.034	1.2	0.080555556	291.9
3 TO C	47.22	0.016	1.2	0.010694444	41
4 TO 5	76.88	0.032	1.2	0.073333333	267
4TO D	76.66	0.01	1.2	0.007222222	26
5 TO 6	66.66	0.032	1.2	0.063611111	231.5
6 TO E	49.60	0.018	1.2	0.015	54.5
6 TO F	51.69	0.032	1.2	0.049722222	179.5
5 TO 7	69.62	0.012	1.2	0.01	34
7 TO G	20.55	0.016	1.2	0.004955674	17.84042
7 TO H	20.73	0.016	1.2	0.005	18

7. COMPARISON OF DIFFERENCE BETWEEN MASS FLOW RATE DETERMINED EXPERIMENTALLY, SWAMY JAIN EQUATION & USING FRICTION FACTOR $F=0.0032+0.210/RE^{0.257}$

Comparison between estimated mass flow rate using friction factor $f=0.0032+0.210/Re^{0.25}$, Swamee Jain friction factor & experimental results are tabulated in **Table-5.**

Table 5 Comparison between estimated mass flow rate using friction factor

$f=0.0032+0.210/Re^{0.257}$, Swamee Jain friction factor & experimental results

Section	**Mass flow rate (Theoretical) Using Kg/hr**	**Mass flow rate (Swamy Jain) Kg/hr**	**Mass flow rate (Experimental)Kg/hr**	**Deviation, %**	
				Theoretical w.r.t experimental a mass flow rate	Using Swamy Jain w.r.t experimental mass flow rate
0-1	382	381.969	381.5	0.131062	0.122944
1 TO 3	332	331.1189	334	-0.5988	-0.86259
1 TO 2	50	49	44	13.63636	11.36364
2 TO A	25	27.61061	32	-21.875	-13.7169
2 TO B	25	27	28	-10.7143	-3.57143
3 TO 4	291.8	291.9	296	-1.41892	-1.38514
3 TO C	40.2	41	43	-6.51163	-4.65116
4 TO 5	266.8	267	261	2.222222	2.298851
4TO D	25	26	31	-19.3548	-16.129
5 TO 6	232	231.5	219	5.936073	5.707763
6 TO E	55	54.5	55.5	-0.9009	-1.8018
6 TO F	177	179.5	180	-1.66667	-0.27778
5 TO 7	34.8	34	32	8.75	6.25
7 TO G	17	17.84042	16	6.25	11.50266
7 TO H	17	18	16	6.25	12.5

From the above table it can be seen large variation in air mass flow rate between experimental results, and mass flow rate estimated using Swamy-Jain equation and using friction factor **$f=0.0032+0.210/Re^{0.257}$**. Hence it is felt a necessary to develop new friction factor which can suit/ matches with the experimental air mass flow rate to design accurate ECS air duct for aerospace industry.

8. GENERATION OF OPTIMISED FRICTION FACTOR FOR AEROSPACE DUCTS

Optimised friction factor equation was derived based on the mass flow rate obtained from the experiment, which gives accurate mass flow rate to design ECS ducts in aerospace industry. Based on the iterative method to obtain exact result w.r.t experimental mass flow rate, following equation of optimised friction factor was obtained:

Optimised friction factor equation $(f_o)= 1000\ \varepsilon / 1.45\ Re^{0.2055}$

Calculated Optimised friction factor at various sections is placed at **Table 6.**

Table 6 Calculated Optimised friction factor at various sections

Section	Theoritical estimated mass flow rate Kg/hr	Length of pipe (m)	Rougness, μm	Fabricated pipe (mm)	Reynold's Number	OptimisedVelocity, m/s	Opimised Friction Factor
0-1	382	0.085	0.00036	36	207448.4	86.91	0.020059
1 to 3	332	0.305	0.00036	36	180461.4	75.61	0.020642
1 to 2	50	0.385	0.00029	14	64236.08	69.20	0.02056
2 to A	25	0.23	0.00029	14	39100.23	42.12	0.022769
2 to B	25	0.062	0.00029	14	38402.01	41.37	0.022853
3 to 4	317	0.175	0.00024	34	167901	74.48	0.013967
3 to C	40.2	0.41	0.0003	16	50708.11	47.80	0.022329
4 to 5	266.8	0.46	0.00024	32	162510.3	76.59	0.014061
4 to D	25	0.375	0.000315	10	56695.33	85.51	0.022913
5 to 6	232	0.14	0.00024	32	141127.4	66.52	0.014474
6 to E	55	0.195	0.000345	18	59519.23	49.87	0.024846
6 to F	177	0.4	0.00024	32	109908.3	51.80	0.015237
5 to 7	34.8	0.46	0.000285	12	53762.81	67.57	0.020959
7 to G	17	0.32	0.0003	16	19672.3	18.54	0.027125
7 to H	17	1.045	0.0003	16	20649.81	19.46	0.026856

Based on above equation, mass flow rate was calculated and tabulated in **Table-7**

Table 7 Estimated mass flow rate at various sections of Aerospace ducts using optimised friction factor

Flow section	Unit Section	D=Inner Dia of pipe(m)	Velocity m/s	Density of Air	Mass flow rate (kg/s)	Revised Mass flow rate based on Optimised friction factor equation (kg/hr)
0-1	-	0.036	86.91	1.2	0.1061	382
1 TO 3	-	0.036	75.61	1.2	0.0923	332.30
1 TO 2	-	0.014	69.20	1.2	0.0127	46
2 TO A	Unit 1	0.014	42.12	1.2	0.0077	28
2 TO B	Unit 2	0.014	41.37	1.2	0.00763	27.5
3 TO 4	-	0.034	74.48	1.2	0.08111	292
3 TO C	Unit 3	0.016	47.80	1.2	0.01152	41.5
4 TO 5	-	0.032	76.59	1.2	0.07388	266
4TO D	Unit 4	0.01	85.51	1.2	0.00805	29
5 TO 6	-	0.032	66.52	1.2	0.06416	231
6 TO E	Unit 5	0.018	49.87	1.2	0.01522	54.8
6 TO F	Unit 6	0.032	51.80	1.2	0.04997	179.9
5 TO 7	-	0.012	67.57	1.2	0.00916	33
7 TO G	Unit 7	0.016	18.54	1.2	0.00447	16.1
7 TO H	Unit 8	0.016	19.46	1.2	0.00469	16.9

Comparison of air mass flow rate flowing in various sections is made between theoretical friction factor ($f=0.0032+0.210/Re^{0.257}$), Swamy-Jain friction factor $=0.25\ [\log_{10}((\varepsilon/3.7D)+(5.74/Re^{0.9}))]^{-2}$

experimental value and Optimised friction factor ($1000\ \varepsilon\ /\ 1.45\ \ Re^{0.2055}$). The Comparative deviation of above three friction factors w.r.t experimental results is tabulated at **Table-8**:

Table 8 The Comparative deviation of mass flow rates based on three friction factors w.r.t experimental results

Section					Deviation, %		
	(Theoretical friction factor) Kg/hr	(Swamy Jain) Kg/hr	(Using Optimised friction factor) Kg/hr	(Experim-ental) Kg/hr	Theoretical w.r.t experimental mass flow rate	Using Swamy Jain friction factor w.r.t experimental mass flow rate	Using Optimsed friction factor w.r.t experimental a mass flow rate
0-1	382	381.969	382	381.5	0.131062	0.122944	0.131061599
1 TO 3	332	331.11	332.30	334	-0.5988	-0.86259	-0.50730926
1 TO 2	50	49	46	44	13.63636	11.36364	4.545454545
2 TO A	25	27.61	28	32	-21.875	-13.7169	-12.5
2 TO B	25	27	27.5	28	-10.7143	-3.57143	-1.78571428
3 TO 4	291.8	291.9	292	296	-1.41892	-1.38514	-1.35135135
3 TO C	40.2	41	41.5	43	-6.51163	-4.65116	-3.48837209
4 TO 5	266.8	267	266	261	2.222222	2.298851	1.91570881
4TO D	25	26	29	31	-19.3548	-16.129	-6.45161290
5 TO 6	232	231.5	231	219	5.936073	5.707763	5.479452055
6 TO E	55	54.5	54.8	55.5	-0.9009	-1.8018	-1.26126126
6 TO F	177	179.5	179.9	180	-1.66667	-0.27778	-0.05555555
5 TO 7	34.8	34	33	32	8.75	6.25	3.125
7 TO G	17	17.84	16.1	16	6.25	11.50266	0.625
7 TO H	17	18	16.9	16	6.25	12.5	5.625

9. RESULTS & DISCUSSION

Estimated mass flow rates based on experimental results has been considered as benchmark to calculate the deviation with respect to estimated mass flow rate calculated using friction factor $f=0.0032+0.210/Re^{0.25}$, Swamy-Jain friction factor $=0.25\ [\log_{10}((\varepsilon/3.7D)+(5.74/Re^{0.9}))]^{-2}$ and Optimised friction factor ($1000\ \varepsilon\ /\ 1.45\ \ Re^{0.2055}$). Result presented at **Table-8** indicates that mass flow rate based on friction factor $f=0.0032+0.210/Re^{0.25}$ has maximum variation w.r.t mass flow rate measured by experiment. The variation of mass flow rate based on Optimised friction factor is minimum w.r.t mass flow rate measured by experiment. However, variation of mass flow rate based on Swamy Jain friction factor (w.r.t mass flow rate measured by experiment) is in between mass flow rate based on friction factor $f=0.0032+0.210/Re^{0.25}$ and mass flow rate measured by optimised friction factor $f_0=1000\varepsilon\ /\ 1.45\ \ Re^{0.2055}$. The largest variation using Friction factor $f=0.0032+0.210/Re^{0.25}$ w.r.t experimental result may be due to non-accounting of average roughness of pipe lines leading to same friction factor for all the duct diameters (ϕ 12 to ϕ 36 mm). Theoretical estimated mass flow rate at various flow sections deviates from 0.131 % to 19.35% w.r.t experimental results. At section 4-D, maximum variation of mass flow rate w.r.t experimental 19.35% has been observed. During this research average roughness of Aerospace duct diameters (ϕ 12 to

ϕ 36 mm) has been measured using Taylor Hobson-Subtonic 3+ Profilometer. The average roughness of these ducts varies from 0.24 µm to 0.345 µm.

Swamy Jain equation has used average roughness of Aerospace ducts to estimate friction factor of partiticular duct diameter. However, Swamy Jain friction factor was not able to predict the results with sufficient accuracy w.r.t Experimental result. Estimated mass flow rate using Swamy Jain friction factor at various flow sections deviates from 0.131 % to 19.35% w.r.t experimental results. At section 4-D, the maximum variation of mass flow rate w.r.t experimental was 16.12%. This has motivated us to optimise the friction factor for Aerospace application so that there should not be any need for validation of theoretically estimated mass flow rates on a test rig .

If we are able to avoid validation of theoretical result on test rig, then there is huge saving in establishment of test rig and further saving in its recurring energy consumption and human resource for running of test rig.

Optimised friction factor equation **$(f_o) = 1000\,\varepsilon / 1.45\ Re^{0.2055}$** has been derived to obtain exact result w.r.t experimental mass flow rate. Estimated mass flow rate using Optimised friction factor at various flow sections deviates from 0.131 % to 12.5% w.r.t experimental results At section 2-A, the maximum variation of mass flow rate w.r.t experimental was 12.5%.

The comparative analysis shown at **Fig 5** (as bar chart) clearly shows that theoretical estimated mass flow rate based on friction factor $f=0.0032+0.210/Re^{0.25}$ varies maximum w.r.t experimental result, However, estimated mass flow rate based on optimised friction factor $f_0=1000\varepsilon / 1.45\ Re^{0.2055}$ varies minimum w.r.t experimental result.

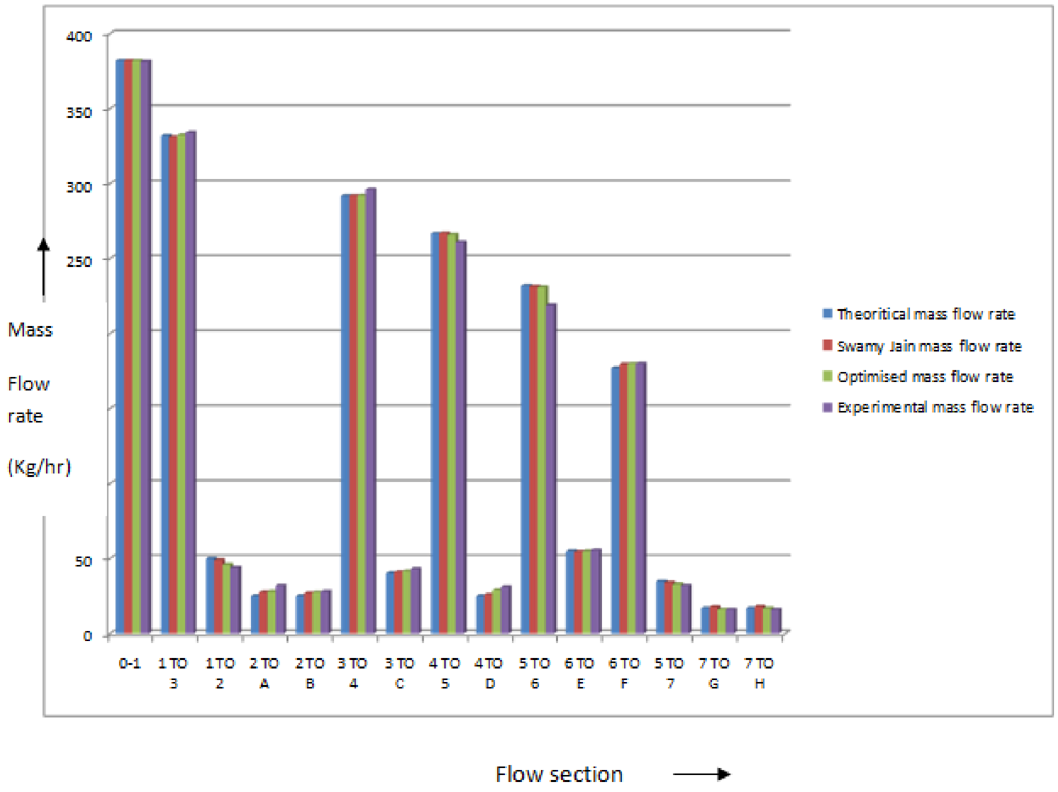


Figure 5 Comparative analysis between Theoretical, Swamy Jain, Optimised and Experimental mass flow rate

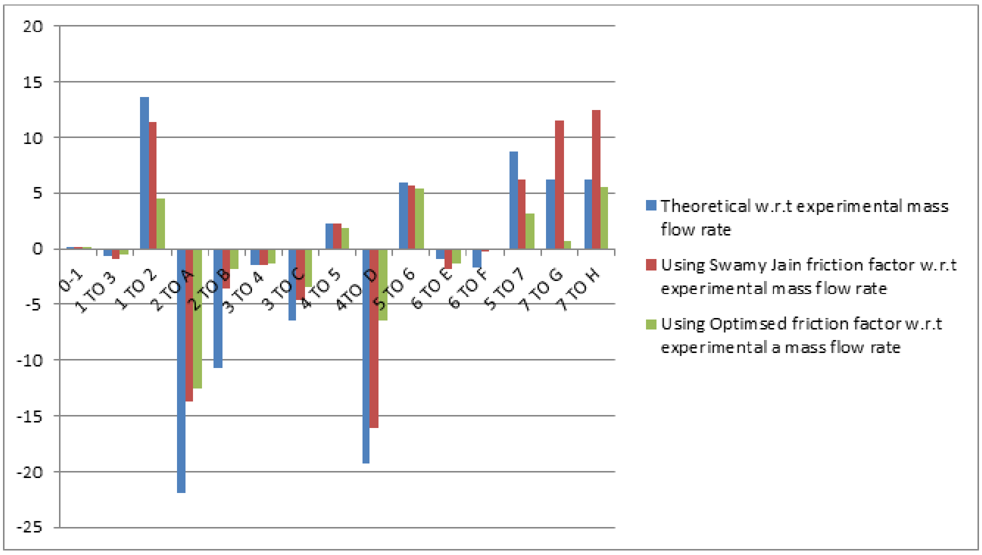


Figure 6 Percentage Deviation analysis between Theoretical, Swamy Jain, Optimised and Experimental mass flow rate

The graph between the percentage deviation in mass flow rate between Theoretical, Swamy Jain, Optimised and Experimental is plotted and observed that the deviation is very less between the mass flow rate calculated by new optimised friction factor and experimental mass flow rate. Hence, this research has predicted that, if optimised friction factor is used in estimating the friction factor of Aerospace ducts, then result will be very close to the realistic.

10. CONCLUSION

This research has generated a new friction factor equation (f_o) = 1000 ε / 1.45 Re 0.2055 $^{\text{for}}$ smooth pipes used in Aerospace application. Average roughness of aerospace ducts made of Aluminium alloy (with variable diameters from ϕ 10 to ϕ 36) has been measured to estimate the Swamy Jain friction factor for smooth pipes. Using mass conservation and energy conservation equation, mass flow rate at various flow sections have been calculated using friction factor $f=0.0032+0.210/Re^{0.25}$, Swamy-Jain friction factor $=0.25\ [\ \log_{10}(\ (\varepsilon/3.7D)+(5.74/Re^{0.9}))]^{-2}$. A test rig has been established to validate the theoretical estimated values at various flow sections. Measurement of air flow rate supplied to various units has been undertaken using thermal mass flow meters. It has observed that theoretical estimated mass flow rate (using friction factor $f=0.0032+0.210/Re^{0.25}$) varies significantly w.r.t experimental results. Estimated mass flow rate using Swamy Jain friction factor are moderately accurate w.r.t experimental results. This variation has created a need of generating a optimised friction factor which can yield flow distribution as close as possible w.r.t experimental results. By iterative method to obtain exact result w.r.t experimental mass flow rate optimised friction factor equation has been generated. This friction factor will eliminate the need of establishment of test rig in future and lead to precious price and time saving. In Future, it is proposed to undertake the CFD analysis to validate to generate correlation between CFD & experimental results for Aerospace ducts.

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