Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.18576/amis/110226

Investigation of High Temperature Cyclic Pressurization of Titanium Ducts

M. Karthigairajan[1,*], *S. Mohanamurugan*[2], *P. K. Nagarajan*[3] *and R. Krishnaraj*[4]

[1] Anna University, Tamilnadu, India
[2] Department Automobile Engineering, Saveetha University, Tamilnadu, India
[3] SA Engineering College, Tamilnadu, India
[4] Centre for Excellence and Incubation, Ambo University, Ethiopia

Received: 4 Dec. 2016, Revised: 26 Jan. 2017, Accepted: 28 Jan. 2017
Published online: 1 Mar. 2017

Abstract: In recent years researchers has taken keen interest in air-conditioning failure occuring at the pneumatic channel of the aircraft which is subjected to hot air pressure cycle, causing the stress developed in the material to be cyclic in nature. Due to the occurence of ice build-up in some parts of the flow channel, to prevent it, pneumatic channel is provided feed with hot air that is bleed from the engine of the aircraft. Mainly titanium is used for pneumatic system components of aircraft due to its favorable characteristics. The crucial part where the failure occurs is taken in to consideration and a new model of the part has been created. CATIA V5 software is used for modeling and thermal analysis is done with the ANSYS software. From the obtained result it is evaluated that the rectangular duct has high heat flux than square and circular ducts.

Keywords: Titanium ducts, duct design, air bleed, air-conditioning, aircraft failure

1 Introduction

Commercial aircraft air-conditioning system set a severe drawback due to ice build-up at various regions of the flow channel. To compensate an additional heating unit is provided to the region where the ice build-up occurs in the duct. The hot bleed air from the engine of the aircraft is routed through the air frame of the pneumatic system to prevent the ice build operation in ducts [3,7]. During the service operation of the pneumatic system, it undergoes high temperature and cyclic pressurization on the components which develop a stress in the material which is cyclic in nature [1,5]. In some cases, failure of the ducts [2,6] has compromised aircraft safety by blowing access panels from the aircraft, causing loss of cabin pressure, and disabling de-icing systems. In other cases, failures have resulted in loud bangs, then entry of hot air plus particles of insulation into the cabin compartment, thereby causing some concern and discomfort. The ducts contain curved, straight sections, joints, welded parts, valves and sensors. The failure due to high temperature cyclic pressure during the service operation of the pneumatic system occurs at welded parts, joints, curves parts, valves and sensors. The crack initiation was also favored by the stress concentration related with the geometry of the ducts.[8] An appropriate design, fabrication and material selection for this system are necessary to guarantee the reliability and durability, which are important factors for the flight safety, maintenance cost reduction and for complying with certification requirement. The various materials that are used for the manufacture of the ducts are galvanized steel, aluminum, glass fiber etc. Among these materials titanium is the material that stands alone, because of its favorable characteristics, such as high strength to weight ratio, corrosion resistance, good formality and appropriate mechanical properties [2]. Titanium has a high operating temperature and thus is used in air distribution system. Pure titanium can withstand an operating temperature of 300^0C. However the failure may be due to the problems in design, manufacturing process, assembly and also due to aging due to service loads.

A large number of failures of the titanium ducts were reported in the area of weld and joints. The crack may be attributed to the residual stress developed due to the weld or due to the prior flaw in the material [4]. There are a large variety of titanium alloys available with each having

* Corresponding author e-mail: karthigairajan.m@gmail.com r.kraj009@gmail.com

Table 1: Chemical composition of titanium material

Element	Amount(max)
C	0.10
O2	0.25
Fe	0.05
N	0.05
H	0.015
Ti	Reminder

distinct properties to stand alone. The mechanical properties of the material that are used for the production plays an important role in the service life of the material. With the aging of the material the mechanical properties of the material may also change as it undergoes variable stress at cyclic temperature and pressure condition. This may lead to the failure of the material. In aircrafts a higher level of design and calculation is required in almost every part of both fabrication and testing which makes it possible to improve and develop a product. The ducts used in aircrafts due to the extreme conditions are facing a flaw at the joints and welded areas. Thus design is mainly concentrated [9,10] on the bents and joints.

The aim of the present work is to find out the optimum design of the air-conditioning duct. Of the many designs available three best suited designs [11,12,13,14, 15,16,17] were selected namely circular, rectangular and square. Analysis were conducted on three types of ducts using an analysis software ANSYS. Thermal analyses were conducted on all the three ducts and results were obtained. The results were compared and a more efficient design is obtained.

2 Materials

2.1 Titanium properties

Titanium is the seventh most abundant metal in the earth's crust, but extracting the material from the oxide in which it occurs naturally is unusually difficult. This makes the titanium the third member of the light alloy trio, by far the most expensive of the three (more than ten times the price of the aluminium). Despite this the use of titanium is growing propelled by its remarkable properties.

2.1.1 Chemical composition

The chemical composition of the titanium as per the SAE AMS 4941C standard is given in Table 1. Titanium metal along with carbon, oxygen, iron, nitrogen and hydrogen constitute the composition of this metal.

2.1.2 Physical properties

The physical properties of the material decide the overall appearance of the material and is shown in Table 2

Table 2: Physical properties of titanium

PROPERTIES	METRIC
Density	450g/cc
Molecular weight	47.867g/mole
STRONGLY IMPORTANT	(4,5,6)
VERY STRONGLY IMPORTANT	(6,7,8)
EXTREMELY IMPORTANT	(9,9,9)

Table 3: Mechanical properties of titanium

Properties	Metric
Tensile ultimate strength	220 Mpa
Tensile yield strength	140Mpa
Elongation	54 Percent
Modulus of elasticity	116 Gpa
Poisson ratio	0.34
Shear modulus	43Gpa

Table 4: Thermal Properties of Titanium

Properties	Metric
Specific heat capacity	0.528J/goc
Thermal conductivity	17 W/mk
Melting point	1650-1670 oc
Boiling point	3287^0c

2.1.3 Mechanical properties

The overall strength, elongation and failure of material are determined by using the mechanical properties. The mechanical properties of Titanium are shown in Table 3.

2.1.4 Thermal Properties

The thermal properties of commercially pure titanium are given in Table 4.

3 Methodology

Three ducts namely circular, rectangular and square were selected based on the equivalent diameter of the circular duct.

3.1 Modelling of circular duct

The circular duct is designed using the CATIA software and the design is analysed using analysis software such as ANSYS to obtain the result. The condition that prevails in the aircraft is brought up using ANSYS and the thermal behaviour of the material is obtained.

The 3D model of the circular duct is modelled using the CATIA software. The detailed steps in the modelling of the duct are given below:

–Initially, the CATIA V5 software was opened.
–Mechanical design-part design from the menu tab was selected.
–Sketching was done on XY axis, inputting circle from the menu with dimension as 50.8mm.
–Another circle with dimension 50.08 was created.
–After finishing sketching operation, YZ axis was selected and a curved path for the duct was created.
–The total length of the line was taken as 200mm with a radius of 76mm.
–After finishing the sketching operation, RIB operation was selected from the tab, and by selecting the two circles and the axis we get the bent cross section of the duct.
–Now by using the pad operation and the two circles that are constructed we can get a circular cross section duct to a length of 350mm.
–Now intersecting cross section of the two operations was deleted, and we get the required duct that is to be considered in this case.

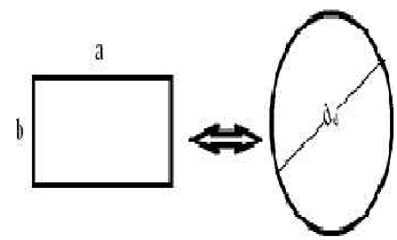
3.2 Modelling of rectangular duct

The 3D model of the rectangular duct is modelled using the CATIA software. The detailed steps in the modelling of the duct are given below:
–Initially, the CATIA V5 software was opened.
–Mechanical design-part design from the menu tab was selected.
–Sketching was done on XY axis, inputting rectangle from the menu with dimension as 52.988 and 26.494mm.
–Another rectangle with dimension 52.268 and 26.134mm was created.
–After finishing sketching operation, YZ axis was selected and a curved path for the duct was created.
–The total length of the line is taken as 200mm with a radius of 76mm.
–Now select the finish sketch operation.
–After finishing the sketching operation, RIB operation was selected from the tab, and by selecting the two rectangles and the axis we get the bent cross section of the duct.
–Now by using the pad operation and the two rectangles that are constructed we can get a rectangular cross section duct to a length of 350mm.
–Now intersecting cross section of the two operations was deleted, and we get the required duct that is to be considered in this case.

3.3 Modelling of square duct

The modelling of the SQUARE using the CATIA software and it is analysed using the ANSYS. The 2D model, 3D model and the analysis is shown below.
–Initially, the CATIA v5 software was opened.
–Mechanical design-part design from the menu tab was selected.
–Sketching was done on XY axis, inputting rectangle from the menu with dimension as 46.1295mm.
–Another rectangle with dimension 45.409mm was created.
–After finishing sketching operation, YZ axis was selected and a curved path for the duct was created.
–The total length of the line is taken as 200mm with a radius of 76mm.
–Now select the finish sketch operation.
–After finishing the sketching operation, RIB operation was selected from the tab, and by selecting the two square and the axis we get the bent cross section of the duct.
–Now by using the pad operation and the two square that are constructed we can get a square cross section duct to a length of 350mm.
–Now intersecting cross section of the two operations was deleted,

Equivalent diameter of a circular duct for a rectangular duct: Let,



a = longest side of the rectangular duct,
b = shorter side of the rectangular duct,
D_{eq}= Equivalent diameter of the circular duct,
A_{eq} = cross-sectional area of the rec. duct = a*b
P_{rect} = wetted perimeter of the rec. duct = 2(a+b)
A_{cir} = c.s area of the equivalent circular duct = $De^{2/4}$
P_{cir} = wetted perimeter of the equivalent cir. duct = De,
a = mass density of air
Q = qty of air passing through the rec. and cir. ducts,
Vel. of air passing through the cir. duct, Ccir = $\frac{Q}{A}cir$
Vel. of air passing through the rec.duct, Crect = $\frac{Q}{A}rect$
Pressure loss due to friction(f) is given as,

$Pf = \frac{fL\rho aC^2}{2m} = \frac{fL\rho a}{2m}(\frac{Q}{A})^2$
and hydraulic mean depth,

$m = \frac{A(c.sareaofduct)}{P(wettedperimeterofduct)}$
Pressure loss due to friction for circular duct,

$$(pf)_{cir} = \frac{fL\rho a}{2(\frac{P_{cir}}{A_{cir}})}(\frac{Q}{A_{cir}})^2 = \frac{fL\rho aQ^2}{2(\frac{P_{cir}}{A_{cir}})^3} \qquad (1)$$

Pressure loss due to friction for circular duct

$$(pf)_{rect} = \frac{fL\rho a}{2(\frac{P_{rect}}{A_{rect}})}(\frac{Q}{A_{rect}})^2 = \frac{fL\rho aQ^2}{2(\frac{P_{rect}}{A_{rect}})^3} \qquad (2)$$

As the pressure loss, friction factor, length, density and density of air for the circular and rectangular duct are the same therefore, from equations (1) and (2).
$\frac{fL\rho aQ^2}{2(\frac{P_{cir}}{A_{cir}})^3} = \frac{fL\rho aQ^2}{2(\frac{P_{cir}}{A_{cir}})^3}$
Rearranging the equations we get,

$$D_{eq} = 1.265[\frac{a^3b^3}{a+b}]^{1/5}$$

Initially a model of each of the duct (circular, rectangular and square) using the CATIA software was created. Then the model is converted in to IGES format for importing to the analysis software such as ANSYS. After saving the model in the IGES format, now import the file in to ANSYS to perform the thermal analysis.

Now, the temperature distribution, total heat flux and the directional heat flux was determined by inputting material properties. From the thermal analysis the value of the maximum temperature, total heat flux and directional heat flux are obtained.

4 Result and discussion

The thermal analysis of circular, rectangular and square ducts is done using ANSYS work bench software. As a result the temperature distribution, total heat flux distribution and directional heat flux distribution are obtained.

4.1 Circular duct

4.1.1 3D Model

The 3-dimensional isometric view of the CATIA modelled circular duct section is shown in Fig. 1.

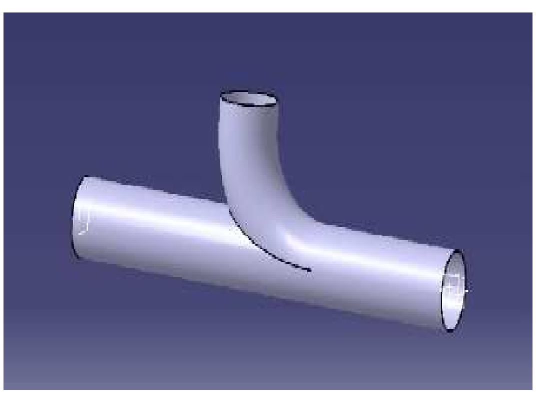


Fig. 1: 3D model of circular duct (isometric view)

4.1.2 Thermal analysis

4.1.2.1 Temperature distribution
The distribution of temperature in the material using ANSYS by inputting temperature at the outer and the inner surface is shown in Fig. 2. A steady state thermal

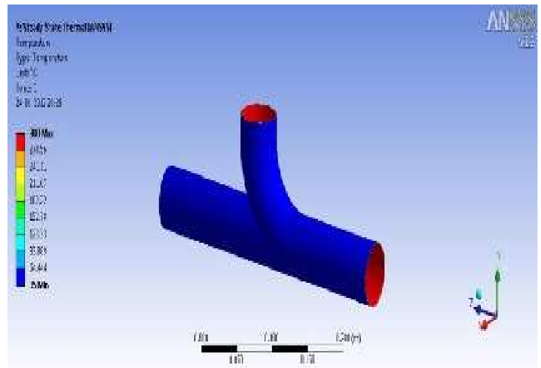


Fig. 2: Temperature distribution in circular duct

analysis using the ANSYS software generates the result as maximum temperature as 300^0C and the minimum temperature of 35^0C which is the outside temperature and inside temperature.
4.1.2.2 Total heat flux distribution
The heat flux distribution in the material along with value of heat flux distribution is shown in Fig. 3. The results

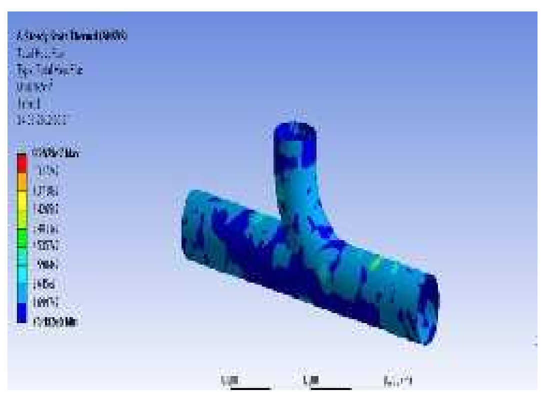


Fig. 3: Total heat flux distribution in circular duct

obtained from the total heat flux distribution are:

The maximum total heat flux in titanium circular duct = $9.2625e^7$

The minimum total heat flux in titanium circular duct = $7.5432e^6$

From the above results it is clear that the total heat flux distribution in the circular duct is uniform along the length of the duct. It shows only slight variations along some points as shown in Fig. 5.

4.1.2.3 Directional heat flux distribution

The direction of heat flux distribution along z axis is shown in Fig. 4. The results obtained from the directional

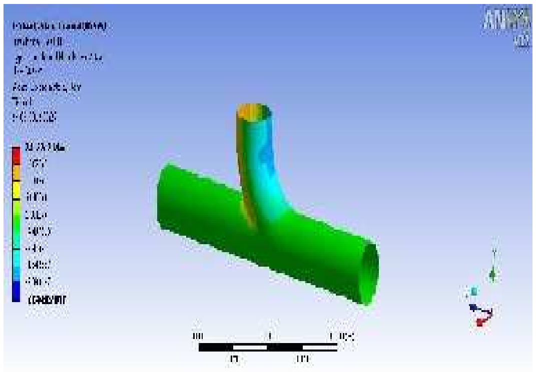


Fig. 4: Directional heat flux distribution in circular duct

heat flux distribution are:

The maximum directional heat flux in titanium circular duct = $2.3137e^7$

The minimum directional heat flux in titanium circular duct = $-2.6443e^7$

From the directional heat flux distribution result that is along the z axis it is clear that the heat flux has uniform value throughout the duct dimension except for the upper end as shown in Fig. 4. It shows some change in heat flux at the end of the duct from maximum to minimum value along z axis from nearer to the farther end of the duct.

The results of the analysis done on circular ducts using Computational Fluid Dynamics (CFD) using Ansys software is given in Fig. 5, Fig. 6 and Fig. 7. The air passing through the circular duct while undergoing a deviation in its path or split path is illustrated. Velocity distribution having difference in value of flow from inlet to outlet is shown in Fig. 10. Pressure distribution having difference in value of flow from inlet to outlet is shown in Fig. 11 and Fig. 12.

i) Velocity Contour:

Velocity distribution in duct is obtained as a result of flow analysis using CFD through circular duct. Sectional plane view of circular duct is shown in the Fig. 10. The result obtained from the velocity distribution of circular duct is:

The maximum flow velocity through duct obtained is 7.5656m/s

Minimum flow velocity obtained is 0 m/sm

ii) Pressure Contour

Pressure distribution in duct is obtained as a result of flow

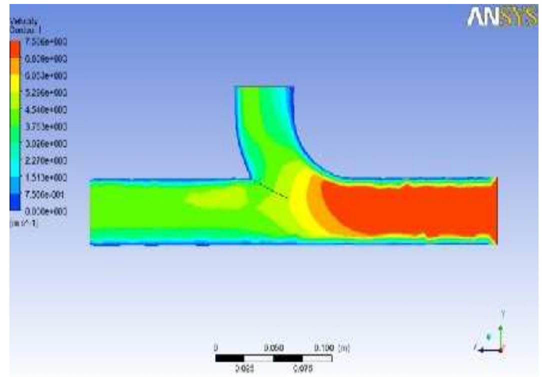


Fig. 5: Velocity distribution in circular duct

analysis using CFD through circular duct. Both isometric view and sectional plane view is shown in the Fig. 6 and Fig. 7. Various values of pressure difference circular duct

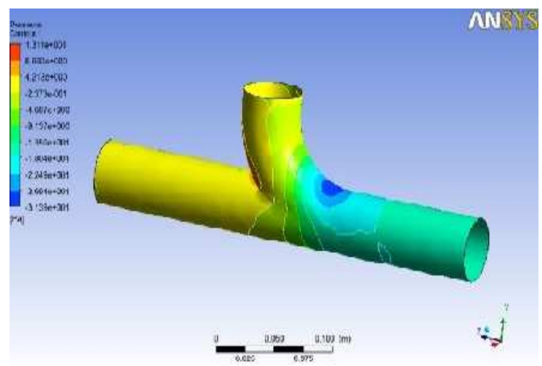


Fig. 6: Pressure distribution in circular duct

is illustrated. The result obtained from the pressure distribution in circular duct is,

Maximum pressure is obtained to be $1.311e^{+001}pa$

Minimum value of pressure is obtained to be $-3.139e^{+001}pa$

4.2 Rectangular duct

4.2.1 3D model

The three dimensional view of rectangular duct modelled by using CATIA software is shown in Fig. 8.

4.2.2 Thermal analysis

4.2.2.1 Temperature distribution

The distribution of temperature in the material using

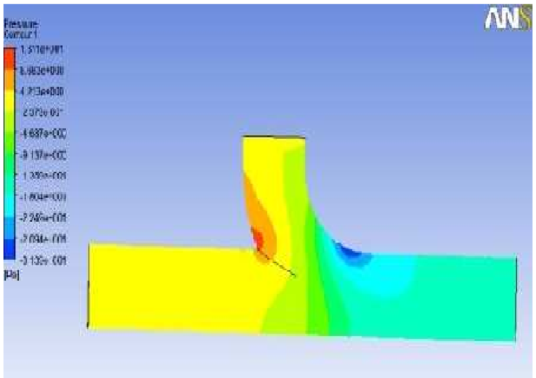


Fig. 7: pressure distribution in circular duct (sectional view)

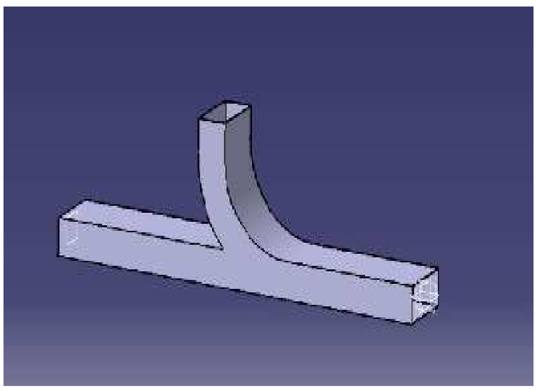


Fig. 8: 3D model of rectangular duct (isometric view)

ANSYS by feeding temperature at the outer and the inner surface is shown in Fig. 9. A steady state thermal analysis

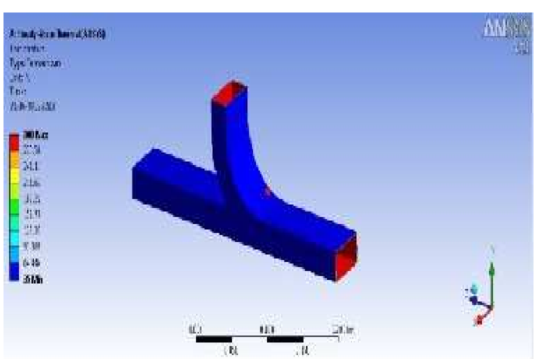


Fig. 9: Temperature distribution in rectangular duct

using the ANSYS software generates the result at a maximum temperature of 300^0C and the minimum temperature of 35^0C which is the outside temperature and inside temperature.

4.2.2.2 Total heat flux distribution

The heat flux distribution in the material along with the value of heat flux distribution is shown in Fig. 10. The

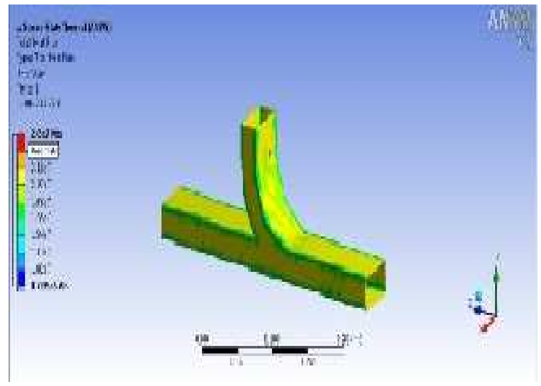


Fig. 10: Total heat flux distribution in rectangular duct

results obtained from the total heat flux distribution are:

The maximum total heat flux in titanium square duct $= 2.86e^7$

The minimum total heat flux in titanium square duct $= 8.7095e^6$ The total heat flux distribution in rectangular ducts is shown in Fig. 10. It is observed that along edges of duct the heat flux value is less than that of the other areas. It is also observed that there is variation in flux value at the bend as shown in Fig. 10.

4.2.2.3 Directional Heat Flux Distribution

The direction of heat flux distribution along z axis is shown in Fig. 11. The results obtained from the directional heat

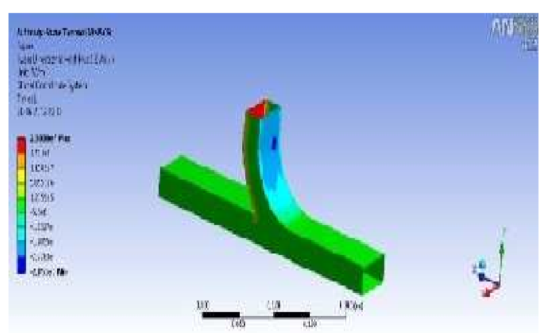


Fig. 11: Directional heat flux distribution in rectangular duct

flux distribution are:

The maximum directional heat flux in titanium rectangular

duct = $2.3038e^7$
The minimum directional heat flux in titanium rectangular duct = $-2.851e^7$

The directional heat flux along z axis of a rectangular duct is shown in Fig. 11. It is observed from the result that heat flux distribution is uniform along the z axis of the duct. There occurs a difference in heat flux value on the section of duct in y axis. The value varies from maximum to minimum as shown in Fig. 11.

The results of the analysis done on circular ducts using Computational Fluid Dynamics (CFD) using Ansys software is given in Fig. 12, Fig. 13 and Fig. 14. The air passing through the rectangular duct while undergoing a deviation in its path or split path as illustrated in Fig. 18. Velocity distribution having difference in value of flow from inlet to outlet is shown in Fig. 18. Pressure distribution having difference in value of flow from inlet to outlet is shown in Fig. 19 and Fig. 20.
i) Velocity Contour:
Velocity distribution in duct is obtained as a result of flow analysis using CFD through rectangular duct. Sectional plane view of circular duct is shown in the Fig. 12.

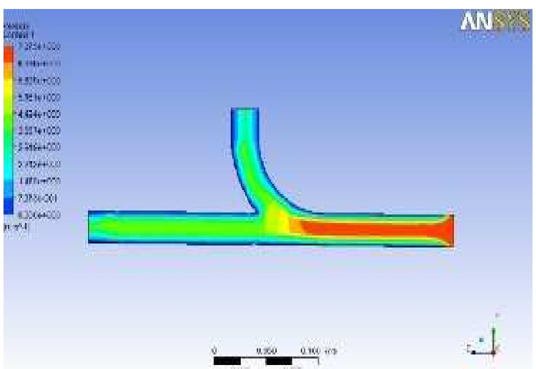


Fig. 12: velocity distribution in rectangular ducts

The result obtained from the velocity distribution of circular duct is:
The maximum flow velocity through duct obtained is 7.373m/s
Minimum flow velocity obtained is 0 m/s
ii) Pressure Contour:
Pressure distribution in duct is obtained as a result of flow analysis using CFD through rectangular duct. Both isometric view and sectional plane view is shown in the Fig. 19 and Fig. 20.

Various values of pressure difference circular duct is illustrated. The result obtained from the pressure distribution in circular duct is,
Maximum pressure obtained to be 8.532 Pa
Minimum value of pressure is obtained to be $-2.204e^{+001pa}$

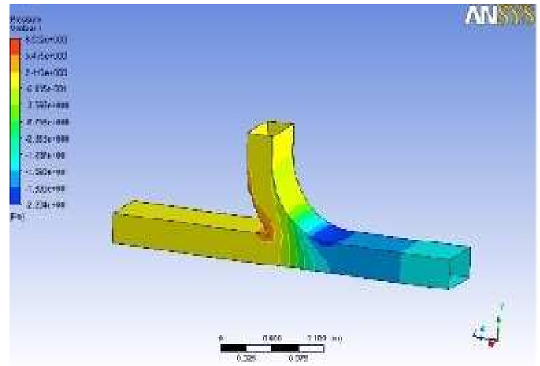


Fig. 13: pressure distribution in rectangular ducts (isometric)

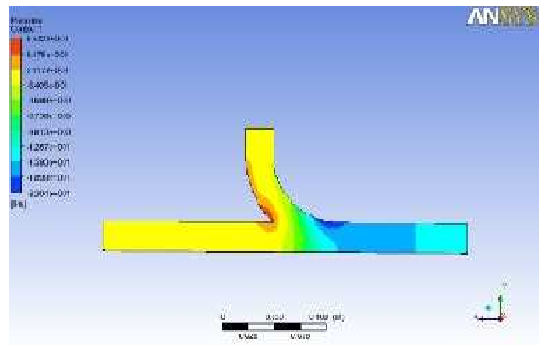


Fig. 14: pressure distribution in rectangular duct (sectional)

4.3 Square duct

4.3.1 3D model

The 3-dimensional isometric view of the CATIA modelled circular duct section is shown in Fig. 15.

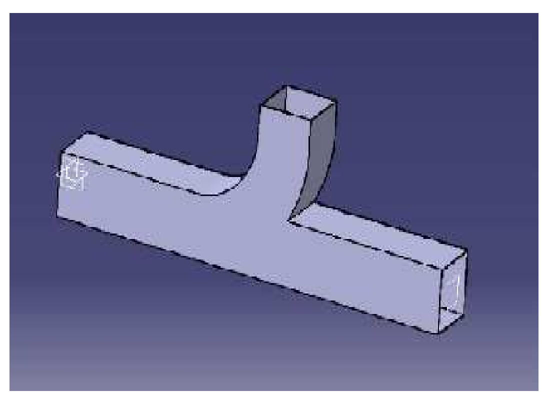


Fig. 15: 3D model of square duct (isometric view)

4.3.2 Thermal Analysis

4.3.2.1. Temperature Distribution
The distribution of temperature in the material using ANSYS by inputting temperature at the outer and the inner surface is shown in Fig. 16.

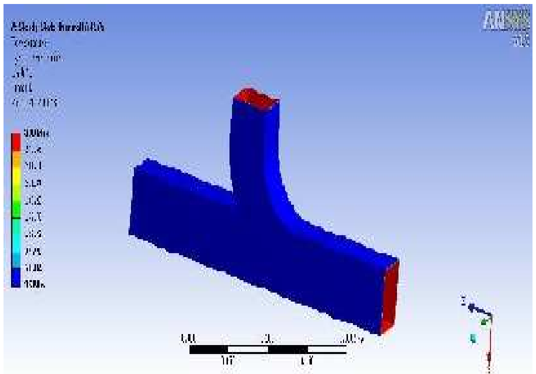


Fig. 16: Temperature distribution in square duct

The results obtained from the total heat flux distribution are:

The maximum total heat flux in titanium square duct $= 300^0C$

The minimum total heat flux in titanium square duct $= 35^0C$

4.3.2.2 Total Heat Flux Distribution
The heat flux distribution in the material along with value of heat flux distribution is shown in Fig. 17.

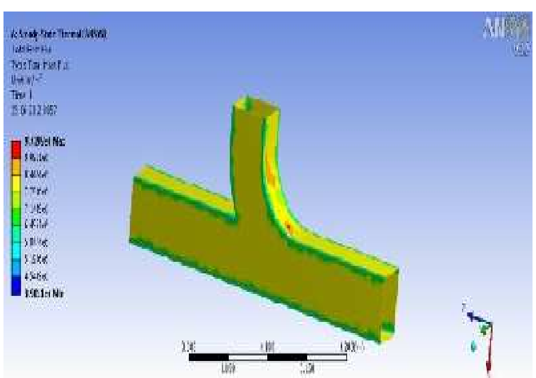


Fig. 17: Total heat flux distribution in square duct

The results obtained from the total heat flux distribution are:

The maximum total heat flux in titanium square duct $= 9.7399e^6$

The minimum total heat flux in titanium square duct $= 3.9011e^6$

The total heat flux distribution in square ducts is shown in Fig. 14. It is observed that along edges of duct the heat flux value is less than that of the other areas. The heat flux on the other part along the duct has the maximum value. Along y axis of the duct, the value is uniform except for the edges which has slight lesser value.

4.3.2.3 Directional Heat Flux Distribution
The direction of heat flux distribution along z axis is shown in Fig. 18.

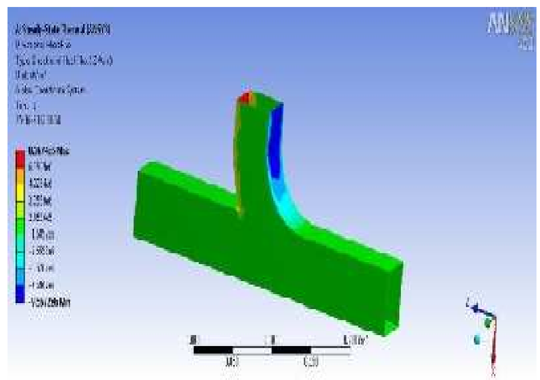


Fig. 18: Directional Heat Flux Distribution in square duct

The results obtained from the directional heat flux distribution are:

The maximum directional heat flux in titanium square duct $= 801674e^{+006}$

The minimum directional heat flux in titanium square duct $= -9.5672e^6$

The directional heat flux along Z-axis of a square duct is shown in Fig. 18. It is observed from the result that heat flux distribution is uniform along the z axis of duct. There occur a difference in heat flux value on the section of duct in Y-axis. The value varies from maximum to minimum as shown in Fig. 16.

Different types of ducts are designed and analysed using Ansys Computational Fluid Dynamic (CFD) software. The flow analysis of different types of ducts is obtained. The results of square duct CFX analysis are velocity through the pipe section and the pressure drop throughout the section.

a) Square Duct
The results of the analysis done on circular ducts using Computational Fluid Dynamics(CFD) using Ansys software is given in Fig. 19, Fig. 20 and Fig. 21. The air passing through the square duct while undergoing a

deviation in its path or split path is illustrated in Fig. 21.

i) Velocity Contour:

Velocity distribution in duct is obtained as a result of flow analysis using CFX through square duct. Sectional plane view of circular duct is shown in Fig. 19. ii) Pressure

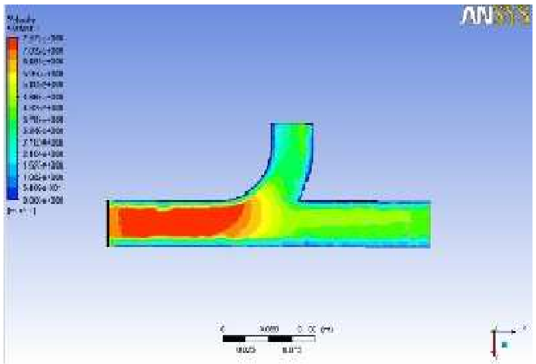


Fig. 19: velocity distribution in square duct

Contour:

Pressure distribution in duct is obtained as a result of flow analysis using CFX through square duct. Both isometric view and sectional plane view is shown in the Fig. 26 and Fig. 27. Various values of pressure difference circular

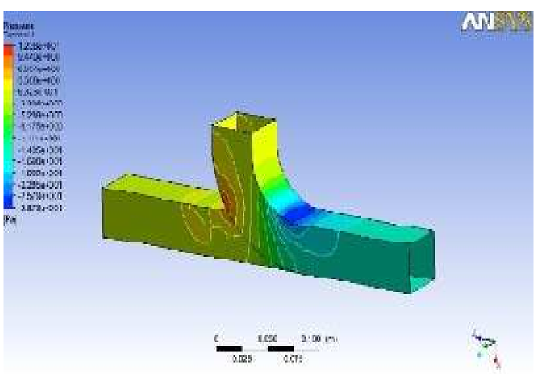


Fig. 20: pressure distribution in square duct(isometric)

duct is illustrated in the figures. The result obtained from the pressure distribution in circular duct is,

Maximum pressure is obtained to be $1.238e^{+001}pa$

Minimum value of pressure is obtained to be $-2.873e^{+001}pa$

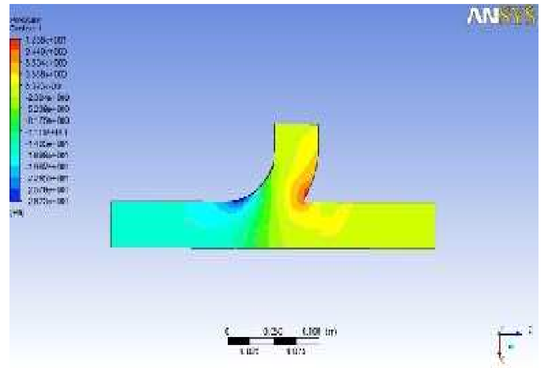


Fig. 21: pressure distribution in square duct(sectional)

4.4 Tabular column

The results of all the three ducts are combined and values of temperature, total heat flux and directional heat flux was tabulated as shown in Table 5.

Result of thermal analysis of three ducts (namely circular, rectangular and square) is shown in Table 5. The maximum and minimum value of temperature, heat flux and directional heat flux is given in Table 5. By using the value a comparison chart of all the three type of duct is created and result is validated.

Table 5: Results of the ANSYS analysis

		Temp.	Total heat flux	Directional heat flux
Circular	Max	300	9.2625e7	2.5137e7
	Min	35	7.5432e6	-2.6443e7
Rectangular	Max	300	2.86e7	2.3038e7
	Min	35	8.7085e6	-2.851e7
Square	Max	300	9.7399e6	301674e6
	Min	35	3.9011e6	-9.5672e6

4.5 Graph

The maximum values of the heat flux of all the three ducts are combined and a graph is drawn as in Fig. 22.

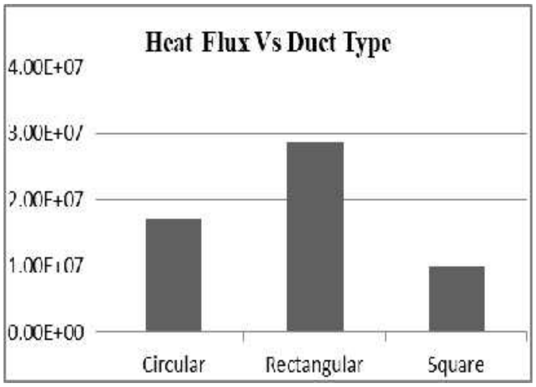


Fig. 22: Total heat flux vs. Duct type

4.5.1 Max heat flux versus the type of duct

The maximum value of total heat flux for a circular duct = $1.6997e^{+7}$
The maximum value of total heat flux for a rectangularr duct = $2.86e^{7}$
The maximum value of total heat flux for a square duct = $9.7399e^{6}$

From graph 1 it is observed that the total heat flux distribution of the rectangular duct is higher than the square and the circular ducts,and the circular duct have low heat flux distribution value. The total heat flux distribution value is plotted along the y axis and type of duct is plotted along x axis.

4.5.2 Max directional heat flux versus duct type

The maximum values of the directional heat flux of all the three ducts are combined and a graph is drawn as in figure 23.

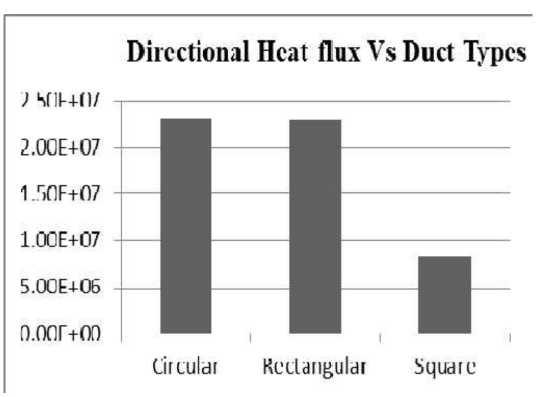


Fig. 23: Direction heat flux vs. Duct type

The maximum value of total heat flux for a circular duct = $2.3137e^{7}$
The maximum value of total heat flux for a rectangular duct = $2.3038e^{7}$
The maximum value of total heat flux for a square duct = $801674e^{6}$

From the readings obtained from Fig. 23, it is clear that the value of directional heat flux of rectangular duct is greater than the other type of ducts. It is also obtained that the circular duct has lowest directional heat flux distribution value

5 Conclusion

Three types of ducts are modelled using the CATIA software and are then analysed using the ANSYS software. The thermal analysis of the three type of ducts are done. The temperature distribution, total heat flux and the directional heat flux values are obtained. The material that is used for this analysis is titanium.

Graphs for the three type of ducts are plotted. It is obtained from the graph that the heat flux value for the rectangular type of duct is higher than that of square and circular ducts. The circular ducts model has the lowest of heat flux distribution value. From the above done thermal analysis of the material it is therefore found that the circular cross-section duct is best suited model as per this analysis is concerned.

The future works that can be performed on air-conditioning duct system have wide scope. Valves, sensors and other joints which are affected by high temperature and cyclic pressure can be analysed.

References

[1] C.A.R.P Baptista, M.J.R Barboza, A.M.L Adib, M. Andrade, C. Otani and D.A.P Reis, Materials and Design **30**, 1503-1510 (2009).
[2] S.M Carvalho, C.A.R.P Baptista and M.S.F Lima, Procedia Engineering **10**, 1321-1326 (2011).
[3] A.M.L Adib, C.A.R.P Baptista, M.J.R Barboza, C. Haga and C.C.F Marques, Engineering Failure Analysis **14**, 1605-1617 (2007).
[4] S.P Lynch, B. Hole and T. Pasang, Engineering Failure Analysis **2**, 1350-6307 (1995).
[5] W. Kuan, B. Yang and M.P Schwarz, Chemical Engineering Science **62**, 2068- 2088 (2007).
[6] Shao L and S.B Riffat, Applied Energy **51**, 0306-2619 (1995).
[7] Samy M.E Behery, M.H Hamed, M.A.E Kadi and K.A Ibrahim, Powder Technology **191**, 130-142 (2009).
[8] C. Ertbruggen, P. Corieri, R. Theunissen, M.L Riethmuller and C. Darquenne, Journal of Biomechanics **41**, 399-405 (2008).
[9] P. Talukdar, C.R Iskra and C.J Simonson, International Journal of Heat and Mass Transfer **51**, 3091-3102 (2008).
[10] J. Zhang and A. Li, Chemical Engineering Research and Design **86**, 95-106 (2008).

[11] K. Rezk and J. Forsberg, Applied Energy **88**, 1596-1605 (2011).
[12] S. Kumar and R.P Saini, Renewable Energy **34**, 1285-1291 (2009).
[13] H. Koskela, Energy and Buildings **36**, 1011-1020 (2004).
[14] A. Barletta, S. Lazzari and E. Zanchini, International Journal of Heat and Mass Transfer **46**, 4499-4512 (2003).
[15] P. Mclver, Applied Ocean Research **20**, 173- 178 (1998).
[16] A.Singh and B.Paul, Journal of Advances in Mechanical Engineering and Science **1**, 14-20(2015)
[17] G.Saravanan, R.Kumar and A.V Kumar, Journal of Advances in Mechanical Engineering and Science **2**, 42-53(2016)

M. Karthigairajan is having 10 years of experience in teaching, one year in industry and a wealth of knowledge. He has organised Conferences, symposiums and workshops. He is now heading the department and established laboratories for Automobile department. He has published articles in 3 Scopus indexed Journals and 7 conferences. He has participated in faculty development programmes organised by NITTTR, Anna University. He has participated in workshops conducted by IIT, Anna University and MIT, Chennai and has completed a short term training programme in Pro-E conducted by CIPET. He has organized social awareness programmes with students. He has a life time membership in ISTE

S. Mohanamurugan has a PhD in internal combustion engines with 15 years of experience in teaching and research in the specialized research area. He has published international peer reviewed journal papers with high impact factors. He held various administrative positions at various engineering colleges and universities.

P.K Nagarajan has a PhD in heat transfer with 17 years of experience in teaching and research and is specialized in the research areas like heat transfer enhancement studies in heat exchanger using augmentation techniques like twisted tape inserts, micro finned tubes and nano-fluids. He is having expertise in designing and conducting experimental heat transfer research problems in heat exchangers, heat sinks design and performance evaluation of various augmentation techniques. He visited University of applied science, Aachen, Solar Institute, Julich Germany and Technical University Eindhoven, Netherlands under European Union Asia link program. He is presently executing DST funded project titled Performance enhancement of micro finned heat exchanger using Nano fluids under Young Scientist Scheme at a worth of 19.38 lakhs and also conducted CSIR funded National level workshop on Nano-fluids Characterization and applications at SAEC on 28.09.12. He also guides four research scholars in the area of energy and nano technology under Anna University, Chennai. He has published papers in international peer reviewed journals with high impact factor. He held various administrative positions like division leader (Thermal and Automotive Group), Evening college coordinator, FFCS coordinator and also worked as Professor and Head in various engineering colleges and universities. He also acted as Chief Superintendent, Camp officer for Anna University during his tenure as Professor at S.A. Engineering College.

R. Krishnaraj is a Gold medalist in engineering design in the Department of Mechanical Engineering, Anna University in the year 2010-2011. He has been honored with Young environmentalist award by Gujarat pollution control board, India and journal of environmental research and development in the year 2011. He has been honoured with the Young scientist Award from the Engineers India, New Delhi in the Year 2013. He has been awarded Inspire fellowship from the Ministry of Science and technology, India and has been honored with Bry Air international Awards for the Excellence in Heating, ventilation Air condition and refrigeration in Feb 2007 and Best NSS National Award by Anna University Chennai, India during the year 2006 2007. He has presented more than 120 papers in international conferences and published 75 papers in international journals. He has been serving as the chief editor and reviewer of many international journals.