Analysis of Heat Transfer Enhancement on Modified Curved Vane Disc Brake by Using OpenFOAM

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***Abstract*—The conventional design of disc brakes has its limitations when it comes to the flow alignment and heat transfer. The main limitations are flow misalignment or formation of high pressure and low pressure regions within the vane channel and the air inflow angle. The flow misalignment and inflow angle plays an important role in mass flow rate and heat transfer within the disc brakes. The flow misalignment factor is controlled by curved vane and its modifications. This work concentrates on the improvement of mass flow rate using modified curved vane with air foil pillars which provide less inflow angle to the air into the channel. The CFD analysis of the model is done using OpenFOAM and the results prove to improve both the mass flow rate and HTC compared to that of the straight radial vanes.**

***Index Terms*—cast iron, CFD analysis, curved vanes, modified, openFOAM**

I. Introduction

Braking is the foremost important safety feature in an automobile which enables the driver not only to stop the vehicle when and where required but also to decelerate and reduce the speed during transit. Braking is also an energy conversion process in which the kinetic energy of the vehicle is converted to heat energy by the application of friction which makes it a thermo mechanical problem too. The temperature of the disc brake during braking is so high and inadequate cooling of the brake can cause formation of TE and Micro hotspots which were studied by Lee et al [12]. Brake disc rotate with high rpms in the air so that the cooling of the disc brake comes under forced convection. The heat transfer coefficient is improved by 50% by using ventilated brake disc when compared to that of solid disc brakes [14].The PIV study done by the study of Adam McPhee[9] reveals that within the ventilated channel of a straight radial vane ,due to the Coriolis effect and the inertia of the entering air flow misalignment occurs. Unlike expected, the air entering is pushed to the trailing side vane of the channel, thereby creates a high pressure region where flow velocity is high and a low pressure region on the leading vane in the direction of rotation. The study also shows the formation of recirculation zone within the vane. This recirculation zone results in flow separation at the tip of the leading vane side. The study also revealed that the formation of the low pressure region reduces flow velocity and thereby creates the chance for laminar boundary layer formation which in effect reduces the heat transfer to the air. K.M Munisamy [2] studied the effect of curved vanes on the disc brakes proved that the flow misalignment of the straight radial vane and reduction in heat transfer coefficient can be reduced by increased mass flow rate produced due to the effect of the curved vanes. F.Talati and S.Jalalifar [7] studied the improvement of the flow using straight radial rounded vanes and found a correlation between heat transfer coefficient and vehicle speed. Heat Transfer Enhancement in Ventilated Brake Disk Using Double Airfoil Vanes by M.Aslani et al. [3] gives improved heat transfer coefficient and flow patterns. T.K.R Rajagopal et al[13] studied different forms of pillar inside the disc brakes instead of vanes, even though some vanes proved to provide more heat transfer area and heat transfer coefficient flow resistance cause the flow to become laminar at low speeds which is not desirable. H.B. Yan et al. [11] studied the effect of cross drilled holes in cooling enhancement of disc brakes, the results shows that the local hotspot formation and propagation enumerated by S.Paneer [12] in (experimental analysis of hotspot propagation in railway discs) is avoided by cross drilled holes. The cross drilled holes allows air to enter into the vanes so that the formation of flow misalignment is reduced and it also helps with the cooling of the friction contact surface also due to the cross flow and turbulence. The cross drilled disc brakes shows22-27% increase in overall Nusselt number than the standard radial vane discs. However the cross drills cannot be used in the cast iron passenger car disc brakes due to the chance for crack formation and failure tendency of the cast-iron when subjected to 4 bar pressure during braking. H.B. Yan [4] studied heat transfer enhancement using X type lattice core which proves 1.1 times more heat transfer area and complex flow mixing gives 14% more heat transfer than the straight radial vanes. However the brake provides 43% more pumping power and complexity in manufacturing tends to decrease the appeal of the superior cooling performance. In this work, the model intended on solving two of the important problems namely flow misalignment and the inflow angle found in the straight radial vane. The curved vanes arrangement along with air foil pillars are used for solving the flow miss alignment problem with least hindrance to the flow as possible. The S Type projection is provided for the air to enter into the vane with least obstruction and acts as a guidance to the flow of the air, which thereby reduce the inflow angle and improve the mass flow rate into the vanes.

II. Theory

In braking operation, the kinetic energy of the vehicle is converted to thermal energy and this induced high temperature in the discs. The temperature rise occurs in the disc brake due to two kind of braking operations. Stop braking is the braking process which causes constant retardation of the vehicle and consequently stopping of the vehicle. This operation occurs in a small amount of time and releases huge amount of energy and it comes under the transient mode of heat transfer. Hold braking is used by a driver when the vehicle going on a decent and to prevent the vehicle from accelerating. This braking helps the driver to hold the vehicle in a constant safe speed in the gradient. The temperature produced is comparatively low compared to stop braking but for a long duration can cause TEI and Hotspot formations. This kind of braking therefore comes under the steady state heat transfer problem.

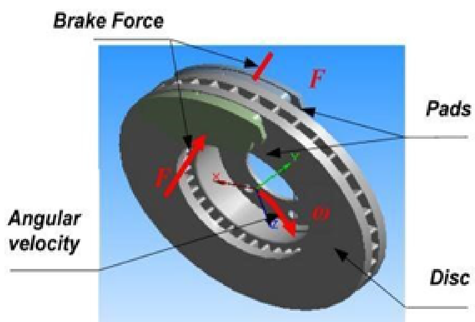

Fig. 1. Disc pads assembly with forces applied to the disc

The heat is produced in the interface of brake pad and brake disc is due to the thermo mechanical conversion of the kinetic energy. The thermal energy is shared by both disc and the pads, the brake pads used in the disc brake operations are generally insulating materials such as asbestos and polymers which does not take much part of the thermal energy so that it is assumed that the conducting metallic disc absorbs and dissipates all the thermal energy produced in the process. There are three mode of heat transfer namely conduction, convection and radiation. The radiation heat transfer occurs without a medium, thermal energy is emitted as quanta of energy in the form of infrared and ultraviolet radiations. The radiation heat transfer is however predominant above 500^oC.the temperature range for the safe operation of the disc brake is below 500^oC, so radiation heat transfer is neglected. Second mode of the heat transfer is the conduction; conduction is the mode of heat transfer within the solids .the thermal energy produced at the friction surface is carried to the other portion of the material .the conduction within the disc materials helps the transfer of the heat from high temperature region of the disc surface to the inner channel region. The conduction within the metal is governed by Fourier equation. The conduction heat transfer plays important role in transient stop braking operations. Third and important mode of heat transfer is by convection heat transfer in transfer of heat from one medium to other occurs by the transport of the fluid medium and is governed by the equation $Q = hA(T_S - T_\infty)$ [1] Where Q is the quantity of heat transferred by A area, T_S is the surface temperature and T_∞ is the fluid bulk temperature. The main mode of heat transfer in a steady state analysis of the brake disc is by convection .the heat produced at the interface is to be convected readily so that the temperature of the disc remains within the desired limit. The heat produced in the interface is conducted by the disc material to the vane channel where the air flow carries the heat by the convection process. The increase in the operating temperature of the disc causes the reduction of the brake friction coefficient which consequently affects the brake efficiency and effective braking distance. However the constant elevated operating temperature of the disc causes the formation of hotspots which drastically reduces the braking efficiency so in order to reduce the high operating temperature whatever heat produced should be transferred using convection in case of a steady state analysis. The transfer of the heat according to equation (1) can be increased by increasing the heat transfer coefficient, increasing the surface area for the convection or by increasing the surface temperature. The surface temperature depends on the conduction of the cast iron material used cannot be varied so the design must be improved using increase in heat transfer coefficient and increased surface area. The temperature at the interface should not exceed over 700^oC, so the input is fixed as 700^oC as thermal input. The heat transfer coefficient and Nusslet number is dependent on the Reynolds number of the flow which is dependent on the flow velocity of air , thermal boundary layer formation and turbulence characteristics of the internal flow . the internal flow of the air is produced due to the rotation of the disc .the centrifugal action creates the flow of the air in the radial direction creates suction pressure at the inlet portion of the disc brake and thereby increases the mass flow rate through the channel. The rotation of the brake disc at constant rpm causes fresh air to enter into the channel and also flow above the braking surface and thereby ensures maximum heat transfer and helps reduce the operating temperature of the disc.

III. Numerical Modelling of the Thermal Problem

From differential, the system is subjected to the following thermal loads:

- A specific heat source Q in [W]
- A voluminal heat source q in $[W/m^3]$
- Temperature imposed (or prescribed) T_P on a surface S_T
- Flux density ϕ_s imposed on a S_ϕ surface in $[W/m^2]$
- Heat transfer by convection ϕ_c on a surface S_ϕ
- Heat transfer by radiation ϕ_r on a surface S_ϕ

The solution of a thermal problem is to find the temperature field T(x, y, z, t) at any point of the solid.

$$\rho C_p T - div(kgradT) - q = 0 \quad (1)$$

Neglecting the radiation term, the energy equation can be written as

$$n \times (kgradT) = \phi_S + h(T_S - T_\infty) \quad (2)$$

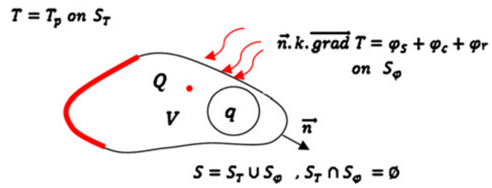

Fig. 2. Mathematical representation

Integrating the differential equation and converting to weak form give following equations.

$$v\int \acute{\rho}C_p dv + v\int gradT(kgradT)dv - \int T(\phi_S + h(T_f - T_\infty) = 0 \quad (3)$$

$$[T]\acute{\rho}C_p + [K]T - F = 0 \quad (4)$$

Where T(x, y, z) = [N] T

$$[K] = v\int [B]T\pounds[B]dv + s\int h[N]T[N]ds \quad (5)$$

$$F = v\int [N]T_q dv + s\int [N]T(S\varphi + hTf) \quad (6)$$

Where [C]=Thermal capacitance matrix (J/K), [K]=Thermal Conductivity Matrix, F= Nodal flux matrix, T= Nodal temperature vector.

Table 1. Boundary Conditions

Boundary	**Boundary Condition**	**Parameters**
Inlet	Pressure, Temperature, Velocity inlet	Atmospheric pressure and temperature, Inlet speed=28km/hr
Outlet	Pressure, Temperature outlet	Atmospheric pressure and temperature
Disc surface	Wall	500K, Thermal properties of cast iron

Table 2. Disc Rotor Dimension

Outer diameter	20 cm
Inner diameter	9 cm
Disc thickness	5 cm
Vane width	2 cm
Vane length	5.5 cm

IV. OpenFOAM Workbench

OpenFOAM is first and foremost a C++ library, used primarily to create executables, known as applications. The applications fall into two categories: solvers, that are each designed to solve a specific problem in continuum mechanics; and utilities, that are designed to perform tasks that involve data manipulation. New solvers and utilities can be created by its users with some pre-requisite knowledge of the underlying method, physics and programming techniques involved.

OpenFOAM is supplied with pre- and post-processing environments. The interface to the pre- and post-processing are themselves OpenFOAM utilities, thereby ensuring consistent data handling across all environments.

Processing tools in OpenFOAM:

- Salome (Drawing + Patch Grouping software)
- SurfaceCheck(Bounding box)
- blockMesh(Griding)
- SurfaceFeatureExtract(Initial meshing config.)
- SnappyHexMesh(Meshing tool)
- chtMultiRegionFoam (solver)
- Paraview (Viewing software)

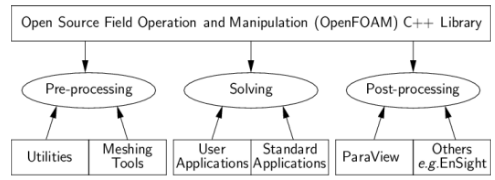

Fig. 3. OpenFOAM (Working)

V. Determination of Heat Coefficient by Convection

A. Introduction

Thermal analysis of the braking system requires a precise determination of the quantity of the heat friction and as well as the distribution of this energy between the disc and the brake lining. When a vehicle is braked, a part of the heat is absorbed by the disc and brake lining. When a vehicle is braked, a part of the frictional heat escapes in the ambient air by convection and radiation. Consequently determination of the heat transfer coefficient is essential. Their exact calculation is however rather difficult, because these coefficient depends on the location and the construction of the braking system, the speed of the vehicle travel and consequently of the air circulation. Since the process of the heat transfer by radiation is not too important, we will determine the convection coefficient (h) of the disc by numerical calculation. this parameter will be exploited to determine the three dimensional distribution of the temperature of the disc.

B. Modeling

The model of the straight radial vane and the novel design is designed using the SOLIDWORKS modeling software. The SOLIDWORKS software is a graphical interfaced software which helps the modeling assembly of the models. The operations such as sketching and adding material can be done simultaneously with graphics helps to design the model easily. The modeled disc geometries are imported to OpenFOAM. The dimensions of the disc are given in the table. The diameter of the disc is made to 20cm for convenience of experimental setup and to accommodate the popular production car disc size.

C. Meshing of the Model

The meshing of the models is done using Open FOAM software and its snappyHexMesh Dict package. The elements used for the meshing of the straight radial vane and new type model are hexahedral three dimensional elements. The model used slice and multi zone method to introduce finer mesh on

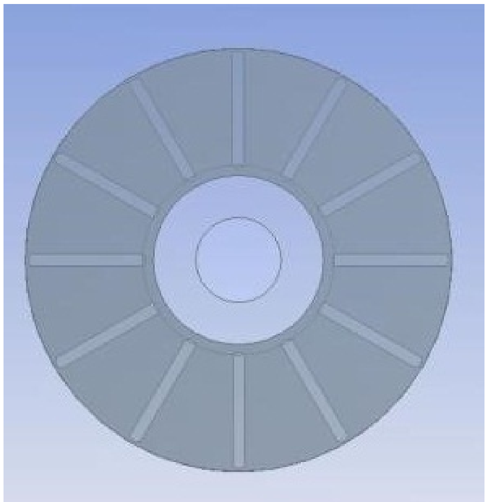

Fig. 4. Isometric view of srv model

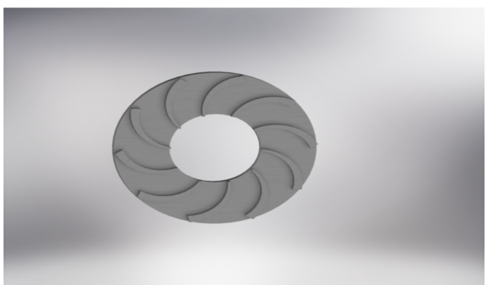

Fig. 5. Isometric view of curved model

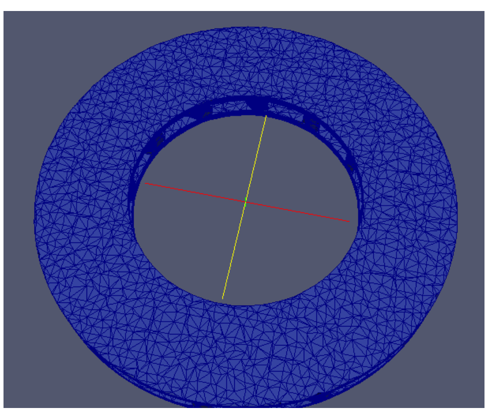

Fig. 6. Isometric view of curved model

the braking surface and coarse mesh on the hub region. The inflation layer of 5 layers is added to capture boundary layer effect of the model. Here the Grids = around 15,00000.

D. Determinations of the temperature velocity and pressure

1) Setup: The disc is situated inside a air domain so that all the surfaces of the disc is in contact with the air surrounding it. The Boolean subtract operation helps to separate the solid disc body from the fluid air body and the interface surface helps connecting the different solid and fluid mesh. The thermal energy model is used for the analysis of the solid disc model and total energy model is used for the analysis of the air domain since it involves viscous heating, rotational kinetic energy and Coriolis Effect. Shear stress transport model is used for the turbulence analysis. The air domain has three surfaces other than the interface; the inlet is opening type since back flow occurs in the vane flow. The outlet is also opening type boundary condition, the air inlet is taken to have 300K .The other symmetry side is wall type offering free slip condition. The thermal input is the input temperature 700K applied on the interface surface of the disc brake.

2) Solver: The solver setup of the OpenFOAM is versatile and allows flexibility for the user for defining the boundary conditions and at the same time the Auto physics setup helps to fix the error in the method used in the modeling. The air domain is moving with air velocity and the disc rotor is kept stationary. The heat flux is applied on the rubbing sides of the disc by defining the disc domain. The translational periodicity method in the mesh interface helps to capture the sliding mesh setup. The time scale factor used for the computation is 0.001.

Fig. 7. Isometric view of the model solver setup

VI. Results and Discussion

A. Influence on the Heat Transfer Coefficient

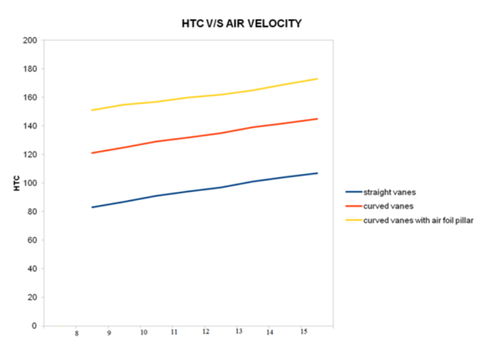

Fig. 8. Plot of heat transfer coefficient vs. Air velocity

The results for the simulation of both models for the required Air velocity plotted against the corresponding heat transfer coefficient. The heat transfer coefficient for the straight radial vane for the different velocity is comparable with that of the other models obtained by different simulations. Here validation is done by mesh independent study. The simulation also verifies the temperature, pressure and velocity regions specified in the experimental literatures. The results of the new model clearly indicate the increased heat transfer coefficient due to the improvement by the model. This is due to the increased mass flow rate and the reduction of the pressure and suction region formation within the channel. The introduction of the modified type self-guiding vanes helps accommodate more air into the channel by reducing the inflow angle the curvature in the vanes of the new model helps improve the pressure difference between the inlet and outlet of the vane. The air foil design of pillars in the model helps to even out the pressure region by creating low pressure region at high pressure region and high pressure at low pressure region. This helps to increase the Reynolds number and thereby the heat transfer coefficient and Nusslet number.

B. Influence on the Heat Transfer Coefficient

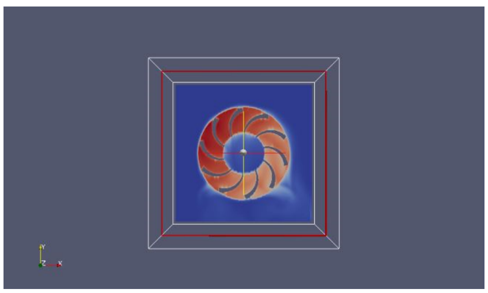

Fig. 9. Temperature plot for curved vane

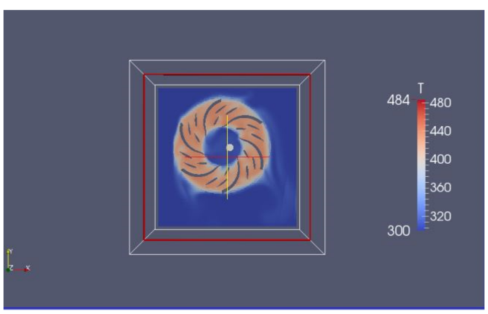

Fig. 10. Velocity plot for modified model

The modeling of temperature in the disc brake will be carried out by taking account of the variation of a certain number of parameters such as the type of braking, the cooling mode of the disc and the choice of disc material. The brake discs are made of cast iron with high carbon content; the contact surface of the disc receives an entering heat flux calculated by the relation. compared to straight and curved vane type disc brake more heat is liberated through new modified model disc brake. it will be reduces the surface temperature of disc rotor.

C. Influence on Velocity

The velocity formation within the vanes of the straight radial vane is shown in the figure. The formation of the

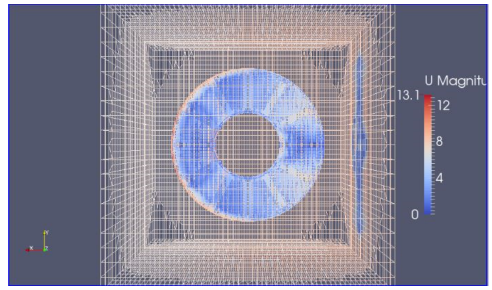

Fig. 11. Velocity plot for straight radial vane

pressure region and the suction region are clearly captured by the paraview code in openFOAM. The inlet is kept as open type since the external air velocity caused by the vehicle motion does not affect the air velocity into the vane channels. increase the velocity inside the channel and maximum outlet velocity is 15 m/s. the model also captures the formation of the recirculation zone at the end of the of the vane The velocity formulation inside the vane channel for the proposed model is shown in the figure. The model shows considerable improvement in the velocity through the vanes .the velocity suction and pressure region formation is reduced the low pressure formation is reduced to minor regions and is localized by the design. The velocity of the air leaving the disc is increased so that the maximum heat forming and heat transfer area of the disc. the edge of the disc is effectively cooled.

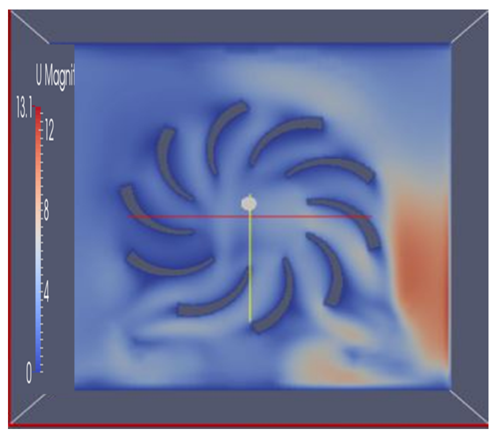

Fig. 12. Velocity plot for curved type

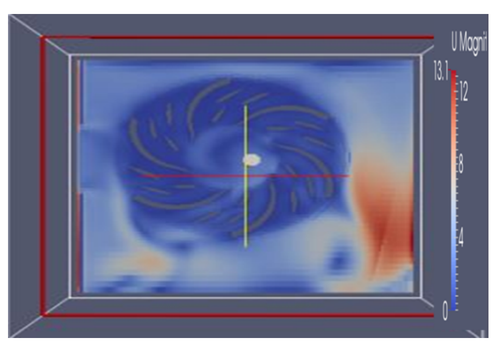

Fig. 13. Velocity plot for modified model

D. Influences on Pressure

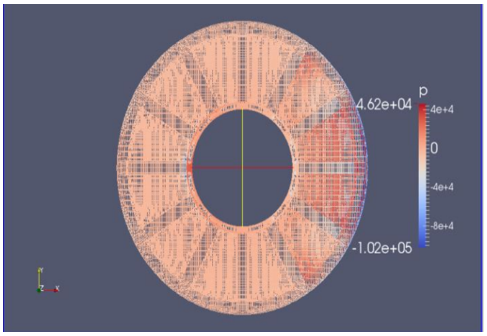

Fig. 14. Pressure plot for straight radial vane

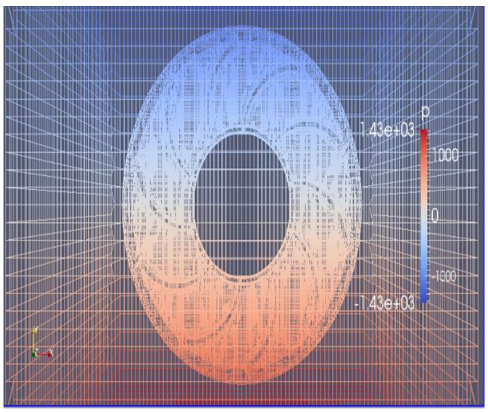

Fig. 15. Pressure plot for curved vane

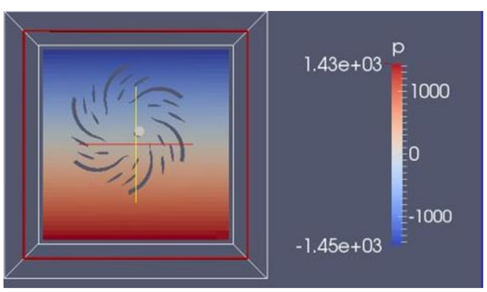

Fig. 16. Pressure plot for modified model

The pressure distribution within the vane channel of the straight radial vane and s type disc are shown in the fig. The pressure distribution curve of the straight radial vane shows the formation of pressure and suction region within the vanes .the region with more air velocity and air density due to the inertia and Coriolis effect is called pressure side which is the right hand side within the vane and the region having low air velocity and density is called suction region. The negative pressure gradient and flow recirculation generally occurs in this region. The pressure distribution curve of the s type vane disc shows the effect of the guide ways .this is shown in the figure the pressure is low at the entry region of the new shaped guide way since the air velocity is higher at these regions. The model helps increase the suction pressure using the air foil design and which is localized at different portion of the disc by the air foil distribution.

VII. Conclusion

In this study, we presented a numerical simulation of the thermal behaviour of a straight radial vane and modified curved vane disc brake in steady state using OpenFOAM. The simulation of the straight radial vane results comparable with that of the modified curved vane results. The validation is done by mesh independent study. The analysis of the new model vane disc brakes shows considerable improvement in the heat transfer coefficient, mass flow rate and velocity distribution. the actual quantity of the heat transfer depends on several parameters such as :

1) Air inlet velocity
2) Conduction and heat transfer by brake pads
3) Method of braking
4) Material Properties

In general the result obtained is satisfactory compared with the results produced by the other works in the field but the In depth understanding of the thermal parameters can only be studied using experimental analysis.

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