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Enhancing Heat Removal by Optimizing Fin Configuration in Air Compressor

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Abstract

This project deals with finding the optimum fin shape and size for the better heat removal from the compressor surface. Various parameters such as fin configuration, fin thickness, length, and number of fins are taken for optimization. Overheating and excess heating causes uneven thermal loading on the compressor surface. This thermally induced stresses can couple with pressure induced stresses and can abruptly alter the life of compressor. Increasing the convective heat transfer is attempted by increasing the surface area and introducing change in configuration of the fin surfaces. This change in configuration converts the fluid from laminar to turbulent or if the flow is already turbulent it enhance the turbulent intensity of the flow. This increases rapid mixing of hot and cold air as well as rate of heat transfer. CFD which finds to be a better alternative for proto based experimental technique is used to compare the thermal pattern over the compressor surface.

Keywords: Fin shape, Laminar flow, Turbulent flow, Computational Fluid Dynamics, etc.

Introduction

Compressor becomes almost an integral part of a mechanical industry and many other commercial applications. The compressed air is used in many applications in modern industries starting from pipeline transport of purified natural gas from production site to consumer, refrigeration, air conditioners, gas turbines, medical, welding, cabin pressurization, breaks almost everywhere we can see its application. The electrical energy used in compressors is not only used to increase the pressure of the fluid (air or gas), it effectively increases the temperature as well. In most cases this heat and temperature is removed by passive means since the temperature rise is not high as IC engines. Still this temperature pattern cause unwanted thermal loading and thermal stresses when this stresses are coupled with flow induced stresses caused because of compression and it will effectively reduce the life of the compressor.

Thus the heat removal rate becomes an essential issue to the compressor designers. Fins that are introduced on the outer surface of the compressor are meant for this purpose. They are meant for increasing the surface area and increase the convective heat transfer rate, on one hand while on the other hand convert the flow laminar to turbulent or if the flow is already turbulent they increases the intensity of turbulent. Thus they increase the rate of effective mixing of cold and hot air and removes heat quickly.

CFD (Computational Fluid Dynamics) is almost replacing proto based experimental techniques with great advantages such as reducing time, cost involved design and it has insight and foresight of the problem.

Air Compressor

An air compressor is a device that converts power (usually from an electric motor, a diesel engine or a gasoline engine) into kinetic energy by compressing and pressurizing air. There are numerous methods of air compression and they divided into either positive-displacement or negative-displacement types.

Convective Heat Transfer

Convective heat transfer often referred to simply as convection, is the transfer of heat from one place to another by the movement of fluids. Convection is usually the dominant form of heat transfer in liquids and gases. Although often discussed as a distinct method of heat transfer, convective heat transfer involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). The term convection can refer to transfer of heat with any fluid movement, but advection is the more precise term for the transfer due only to bulk fluid flow. The process of transfer of heat from a solid to a fluid, or the reverse, requires not only transfer of heat by bulk motion of the fluid, but also diffusion/conduction of heat through the still boundary layer next to the solid. Thus, this process with a moving fluid requires both diffusion and advection of heat, a process that is usually referred to as convection.

Newton's Law Of Cooling

Convection-cooling can sometimes be described by Newton's law of cooling in cases where the heat transfer coefficient is independent or relatively independent of the temperature difference between object and environment. Newton's law, which requires a constant heat transfer coefficient, states that “the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings”. Newton's cooling law is a solution of the differential equation given by Fourier's law:

$$\frac{dQ}{dt} = h \cdot A(T(t) - T_{\text{env}})$$

Where, Q is the thermal energy in Joules

h is the Convective heat transfer coefficient in W/m^2 K

A is the surface area of the heat being transferred in m^2

T is the temperature of the object's surface in K

T_{env} is the temperature of the environment in K

Nusselt Number

In heat transfer at a boundary (surface) within a fluid, the Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary. In this context, convection includes both advection and diffusion. Named after Wilhelm Nusselt, it is a dimensionless number. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. A Nusselt number close to one, namely convection and conduction of similar magnitude, is characteristic of "slug flow" or laminar flow. A larger Nusselt number corresponds to more active convection, with turbulent flow typically in the 100–1000 range.

The convection and conduction heat flows are parallel to each other and to the surface normal of the boundary surface, and are all perpendicular to the mean fluid flow in the simple case.

$$\mathrm{Nu}_L = \frac{\text{Convective heat transfer}}{\text{Conductive heat transfer}} = \frac{hL}{k_f}$$

Where,

h = convective heat transfer coefficient in W/m^2 K

L = characteristic length in m

k_f = thermal conductivity of the fluid in W/mK

Heat Transfer Coefficient

The heat transfer coefficient or film coefficient is used in calculating the heat transfer, typically by convection or phase transition between a fluid and a solid:

$$h = \frac{Q}{A \cdot \Delta T}$$

Where,

Q = heat flow rate or heat transfer rate, J/s = W

h = heat transfer coefficient, W/m^2K

A = heat transfer surface area, m^2

ΔT = difference in temperature between the solid surface and surrounding fluid area, K

From the above equation, the heat transfer coefficient is the proportionality coefficient between the heat flux, i.e., heat flow rate per unit area, $q = Q/A$, and the thermodynamic driving force for the flow of heat (i.e., the temperature difference, ΔT). There are numerous methods for calculating the heat transfer coefficient in different heat transfer modes, different fluids, flow regimes, and under different thermo hydraulic conditions. Often it can be estimated by dividing the thermal conductivity of the convection fluid by a length scale. The heat transfer coefficient is often calculated from the Nusselt number (a dimensionless number).

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is the science of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena

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by solving the mathematical equations which govern these processes using a numerical process.

Governing Equations of CFD

Applying the fundamental laws of mechanics to a fluid gives the governing equations for that fluid. The conservation of mass equation and the conservation of momentum equation are combined along with the conservation of energy equation to form a set of coupled, nonlinear partial differential equations. It is not possible to solve these equations analytically for most engineering problems. However, it is possible to obtain approximate computer-based solutions to the governing equations for a variety of engineering problems. This is the subject matter of Computational Fluid Dynamics (CFD).

Conservation of mass:

Rate of increase of mass in fluid element equals the net rate of mass flow into the element.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

For incompressible fluid flow….,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

Conservation of momentum:

Momentum is conserved in x, y, z direction & from the Newton's second law (F=ma) the momentum equations in all three direction is derived as,

$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u\mathbf{V})=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+\rho f_x$$

Conserved in X direction

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v\mathbf{V})=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+\rho f_y$$

Conserved in Y direction

$$\frac{\partial(\rho w)}{\partial t}+\nabla\cdot(\rho w\mathbf{V})=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+\rho f_z$$

Conserved in Z direction

Observations

Existing Configuration of Fin

1. No of fins (N) = 10
2. Thickness of fins (T) – 3 mm
3. Length of fins (L) – 45 mm

The following observations were found from the analysis:

- Maximum heat energy produced is 131340.6 W/m³
- Maximum speed of the compressor fan is 864 rpm
- The maximum temperature obtained on the cylinder is 345K at the rear side of the cylinder

Velocity and temperature distribution details are tabulated as follows:

Sl. No	Parameter	Cylinder Head	Cylinder Front side	Cylinder back side
1	Velocity of air (m/s)	1.032	4.473	1.0323
2	Convective heat transfer coefficient (W/m²K)	34.57	25.91	12.45
3	Maximum temperature (K)	342	330	345

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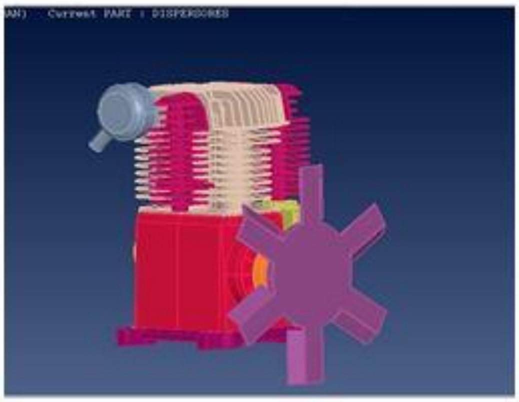

Figure 1: CAD Model of Compressor

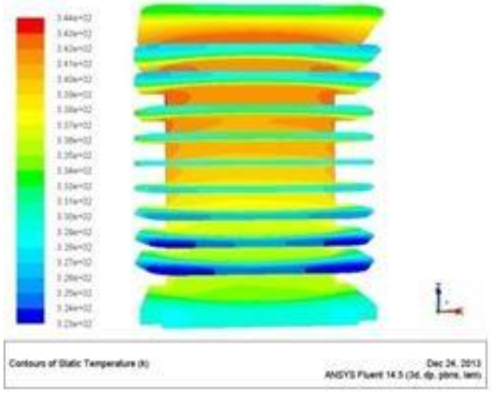

Figure 2: Temperature distribution on the front side of the cylinder

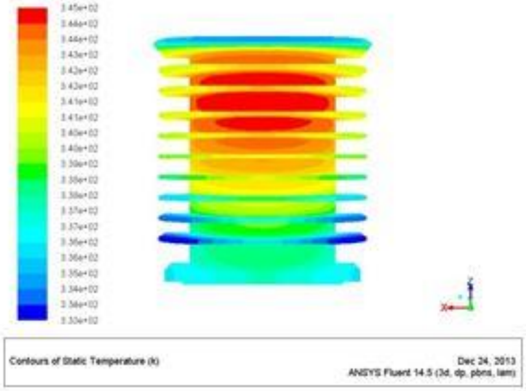

Figure 3: Temperature distribution on the back side of the cylinder

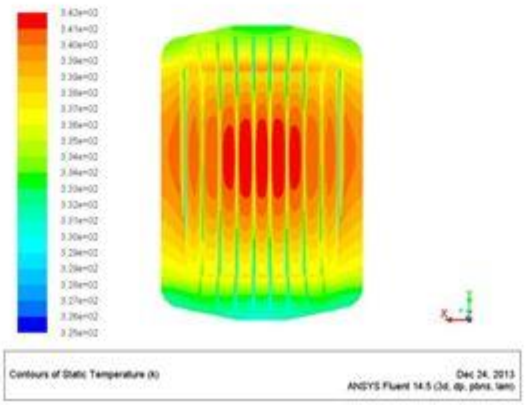

Figure 4: Temperature distribution on the Head of the cylinder

Modification and Analysis

The following parameters are taken for modification and three different combinations of fin configurations are selected for analysis.

Trial No.	No. of fins (N)	Thickness of fins (T)	Length of fins (L)
1	10	3.5	47
2	10	3	49
3	10	2.5	51

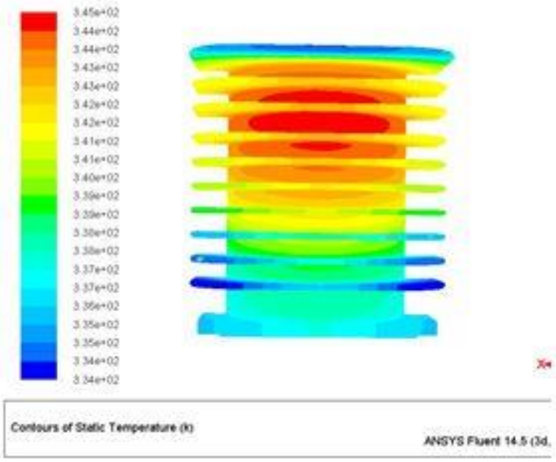

Figure 5: Trial 1 - Temperature distribution on the back side of the cylinder

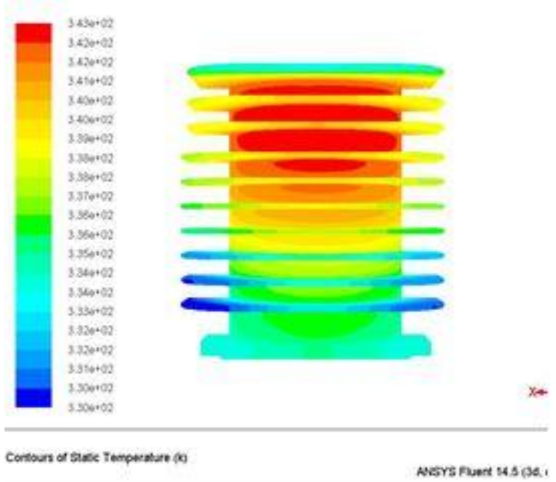

Figure 6: Trial 2 - Temperature distribution on the back side of the cylinder

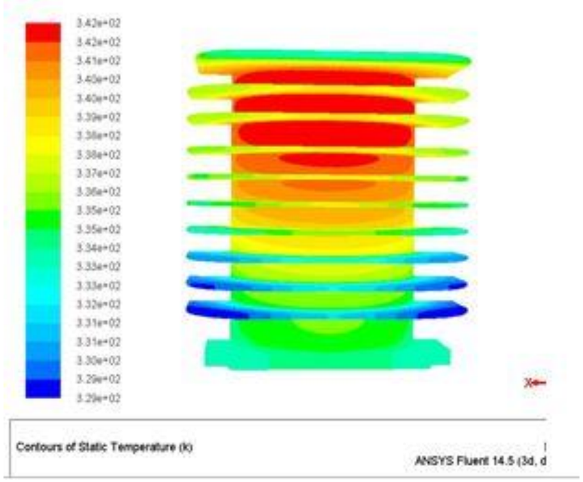

Figure 7: Trial 3 - Temperature distribution on the back side of the cylinder

RESULT COMPARISON

Trial No.	No. of fins (N)	Thickness of fins (T, in mm)	Length of fins (L, in mm)	Max. temperature obtained (in K)
Existing	10	3	45	345
1	10	3.5	47	345
2	10	3	49	343
3	10	2.5	51	342

Conclusion

The Computational Fluid Dynamics (CFD) is utilized to achieve the instantaneous pattern of local velocities and local heat transfer coefficients over the compressor surface. This heat transfer coefficient values are used as the input for thermal analysis and the thermal distribution of the compressor for the base geometry. It was found that the temperature in the areas of fan influence has less values than the rear side. The maximum temperature found on the rear side of the compressor cylinder is 345K (72^{0}C) but in the front side of the cylinder it was found that 330K (57^{0}C). After the modification and analysis of fin configuration, it was found that the maximum temperature obtained on the compressor surface was minimized and the temperature value is 342 K (69^{0}C). So that the temperature difference was minimized by modifying the fin configuration.

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