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Design and Optimisation of Cooling System for Tracked Vehicle Powerpack

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ABSTRACT

Military tracked vehicles are deployed in severe environmental and loading conditions during military operations. The space availability and high heat rejection sources makes the cooling system design a challenging task by offering little margin in design parameters. Prime aspects of the design methodology, i.e. packaging of cooling system aggregates in available space, optimising air flow, numerical simulation and also the evaluation of cooling system performance on a test bench in simulated vehicle conditions and during field trials are presented. During preliminary design stage virtual prototyping approach was adopted which helped to make critical decisions earlier in the development stage before physical prototyping. Further, sensitivity study of size of heat exchangers, layout of fan-heat exchangers and its effect on overall system resistance was studied. Data from field trials were gathered and analysed. A good correlation of thermal data from field trials in collaboration with CVRDE and data evaluated based on numerical simulations is established. This approach and close correlation between the theoretical and field data will be helpful in achieving all future developments of tracked vehicle powerpacks, first time right.

Keywords: Tracked vehicle; Military vehicle; Cooling system; Radiator; Charged air cooler; Hydraulic oil cooler; Powerpack; Numerical analysis; Simulation; Digital prototype

1. INTRODUCTION

Military tracked vehicles go through severe environmental and loading conditions during military operations. To get enhanced mobility during cross country operations, there is a requirement to upgrade the vehicle engine. When the engine gets upgraded, the associated subsystems viz. transmission upgrade, cooling system upgrade and air filtration system upgrade are also imperative. Moreover it is required to fit the new powerpack with the cooling system in the same engine compartment of existing vehicle. In such conditions, the cooling system becomes a critical part since its performance is closely connected to the combat effectiveness, endurance and survivability[4]. To protect the vehicle systems against different threats, viz. small-arms, mines, splinters, all vehicle subsystems including powerpack are located in a completely enclosed compartment with limited ventilation only from top and in some cases rear end. This offers very limited space availability for the cooling system. Also cooling air flow path has highly restricted ballistic louvers, and exhibits change in cross section areas due to packaging constraints. The high ambient temperatures in desert conditions add to that thereby making the enclosed engine compartment temperatures much more than the ambient. The dust concentration in the air is high during summer which clogs the cooling system. These aspects make the cooling system design a challenging task by offering very little margin in design parameters, especially in the desert environment. These challenges have been addressed while designing the cooling system.

The prime aspects of the design methodology of an upgraded powerpack, i.e. the packaging of cooling system aggregates in the available space, optimising air flow, estimation of system resistance, numerical simulation and evaluation of cooling system performance on a test bench and during field trials are presented. All design aspects discussed in this paper are for one of the powerpack developments done by Larsen & Toubro Limited for Combat Vehicles Research and Development Establishment (CVRDE). This powerpack performance was validated during field trials in desert.

The cooling system comprises of heat exchangers/ radiators, duct, fan/s, louvers and control unit. More than one design variants are possible based on fan-radiator arrangements. These variants are evaluated based on several attributes like overall resistance to air flow, available surface area for radiators, fan location, orientation, packaging constraints and maintainability aspect. All attributes are weighted against each other in weighted matrix and one of the design alternatives was finalised for the detailed design.

2. HEAT SOURCES IN POWERPACK

In the powerpack, engine is cooled by the coolant. The transmission gear box is cooled and lubricated by the transmission oil, which again is cooled by the engine coolant in transmission oil cooler (TOC).

Main heat sources / heat carrying elements involved in the

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powerpack are coolant, engine body, charged air, transmission body, transmission oil and hydraulic oil. This heat needs to be extracted through a complex set of heat exchangers. Some part of air ventilation is needed in the compartment for maintaining the compartment temperature within limit for the general health of components & also for the associated electronics. Simplified coolant circuit in the powerpack is as shown in Fig. 1.

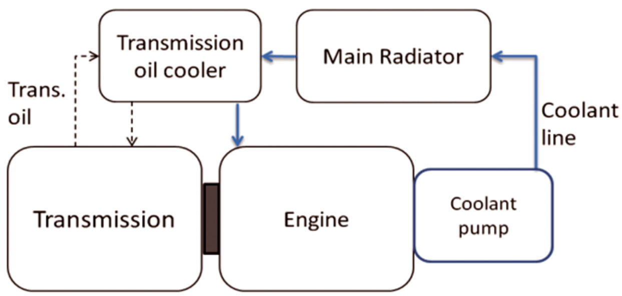

Figure 1. Coolant circuit.

Fan is provided to circulate the air through these heat exchangers. These are principally air cooled heat exchangers where cooling medium is ambient air. Fan supports rated air flow through these heat exchangers overcoming the pressure losses in the system. Fan draws ambient cooling air through these heat exchangers. The system is designed for operation in environmental conditions ranging from -20 °C to 55 °C. As discussed earlier, the high ambient temperatures in desert conditions add to the heat thereby making the enclosed engine compartment temperatures much more than the ambient. For the higher effectiveness of heat exchangers, it is essential to ensure that rated air flow is going through them. There are various design approaches for cooling system layout with its pros and cons. In this paper, closed ducting approach is adopted for cooling system so as to ensure required flow rate.

To protect the vehicle systems against different threats viz. small-arms, splinters, the engine compartment is covered with ballistic louvers. So the duct arrangement, intake and outlet louvers also become the important parts of cooling system.

In the initial design stage, viable space for cooling system was allocated. Main constraints for allocating space envelop were arrangement of engine-transmission assembly, amount of heat rejection in given volume, position of engine exhaust, position of crew, accommodating cooling system before glacis plate, ballistic requirements, direction of fan exhaust. Indicative volume for cooling system is as shown in Fig. 2.

Figure 2, the envelop shown is available for cooling system in an engine compartment after placing engine and transmission at its place. Location of all the heat exchangers, fan and its size should also be taken into consideration.

3. COOLING SYSTEM LAYOUT

Based on weighted matrix, one layout design of cooling system was finalised and considered for detailed design. Attributes for weighted matrix were space, orientation of heat exchangers & fan, available area for airflow through heat exchangers, resistance to airflow, maintainability and ballistics. Considering assembly constraints, heat dissipation

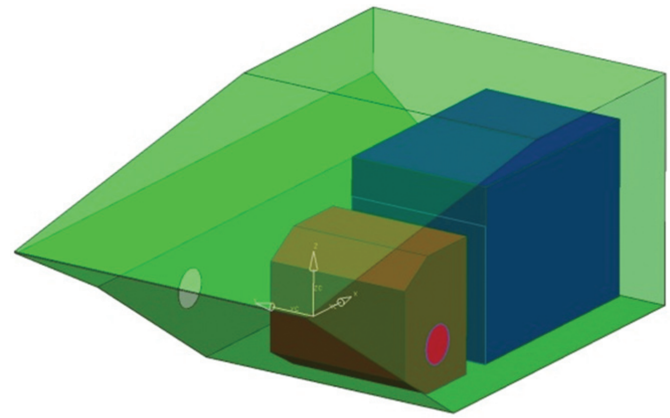

Figure 2. Space envelop for cooling system.

capacity of heat exchangers and the available surface area at the top, approximate sizing (volume) of heat exchangers was done. Volume for duct was extracted such that there will not be any interference between the engine and transmission walls and also it will not obstruct the other structural members and piping inside the engine compartment. Target temperature rise on air inlet side (cold side) was set and considering the ambient temperature of 55 °C, air outlet side temperature (cold side) was arrived at. Considering this allowable rise in temperature, the mass flow rate of air required for various radiators/ coolers was calculated. Fan was considered to operate in pull mode based on layout design which would pull the air from heat exchangers and throw it in atmosphere. Rated air flow and the pressure rise are the two parameters that are essential to decide the fan operating point. Depending upon the operating point of fan, fan power was estimated.

Intake louvers, radiators, duct and outlet louvers offer resistance to air flow. For radiators, pressure loss data for rated flow was experimentally collected. Pressure drop data through duct and louvers was not available which in fact has significant contribution to overall system resistance. So primarily CFD analysis was performed to estimate the pressure loss across intake, outlet louvers, and duct. Sensitivity study of shape, pitch and distance from fan in case of intake and outlet ballistic louvers was also performed.

4. CFD ANALYSIS

CFD simulations solve fundamental equations of fluid dynamics, over small control volumes. These control volumes are created by discretising the domain. Grid size created for the domain of intake louvers, duct and outlet louvers was about 0.4, 3 and 2 million cells respectively. Commercial software solves Reynold Average Navier Stokes equations for general purpose flows in conjunction with turbulent models. K-Epsilon turbulent model with standard wall functions was used in following analyses which is more suitable for practical engineering flow calculations. Since flows are turbulent in nature, wall y^+ was maintained from 30 to 300 for selected turbulent model. Main objective of the analyses depicted in this paper was to estimate system pressure loss and therefore energy equations were not incorporated during computation.

4.1 Intake Louvers

Ballistic intake louvers were considered for assessment of pressure loss. Profile for ballistic louvers was obtained from CVRDE. The louver area has been derived from the area required for cooling air flow. The louver pitch/height ratio has been maintained as that of the existing vehicle in order to retain the vehicle ballistic requirements.

These louvers are designed to provide maximum protection against attack for powerpack compartment. But its functional requirement is as opposed to its other purpose of allowing maximum flow passage for air to flow through, so they offer more resistance to air flow than normal louvers. Loss coefficient characteristics were established for different flow rates. Representative louver profile considered for analysis is as shown in Fig. 3.

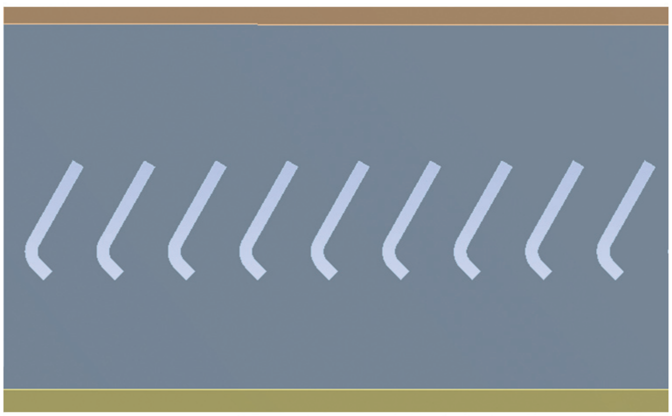

Figure 3. CFD domain - intake louvers.

Preliminary CFD results were benchmarked against the known pressure loss data obtained from handbook[1], for straight profile louvers. Then same method is applied to analyse pressure loss through ballistic louver profile. CFD analysis was carried out for ballistic louver profile for different velocities and then pressure loss data was obtained. Following Fig. 4 shows the velocity vector plot obtained from CFD analysis. In similar manner pressure loss data for different velocities is as shown in Fig. 5.

From this data, it can be concluded that pressure drop is directly proportional to the square of velocity. This equation for pressure drop for intake louvers was used in estimation

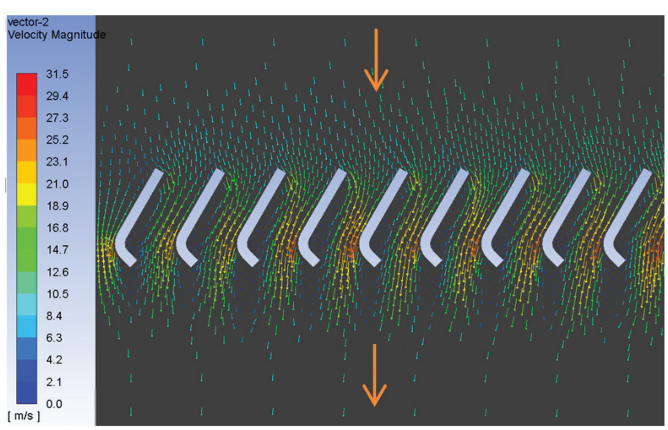

Figure 4. Velocity vector plot.

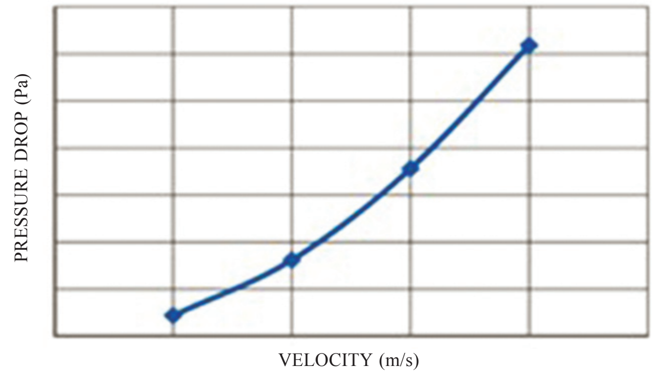

Figure 5. Pressure loss *vs* intake velocity.

of total system resistance. In some situations to protect compartment from outside threats it is necessary to change the angle of louvers. For this scenario further study was carried out to check the sensitivity of angle of louvers on pressure drop. Angle of louvers was varied and pressure drop was obtained and as shown in Fig. 6.

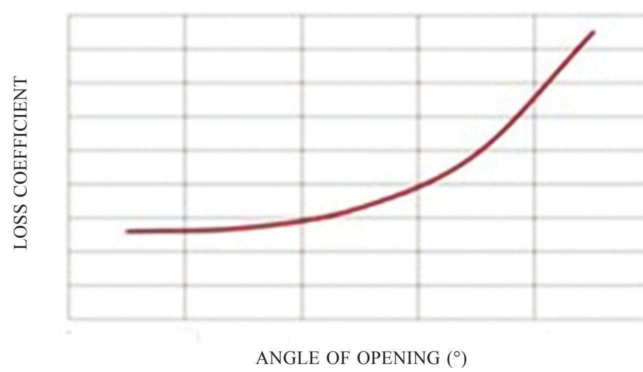

Figure 6. Pressure loss coefficient vs. louvers' opening angle.

4.2 Duct

A dedicated duct has been provided for air to flow from radiators to fan. Shape of the duct was derived based on available volume to accommodate in powerpack compartment and leaving a space for other aggregates within the compartment. Basic CAD model was created for duct and taken for analysis purpose. For CFD analysis the fluid domain was created for preliminary duct geometry. Boundary conditions given are pressure inlet and the fan is defined as pressure outlet with specified mass flow rate. Heat exchangers were modelled as porous zone. Grid convergence study was performed to finalise the grid size and refinement. Results from CFD analysis are presented in following Fig. 7.

It was observed that the inlet velocity distribution over radiator was not uniform and has variation of about 10 per cent along the length. Further iterations were carried out to optimise duct geometry and to select best compromises for satisfactory configuration which will incur minimum flow losses.

4.3 Outlet Louvers

Air velocities near outlet louvers were higher since the fan was located below it. It became essential to model velocity components of fan flowing through outlet louvers to get the

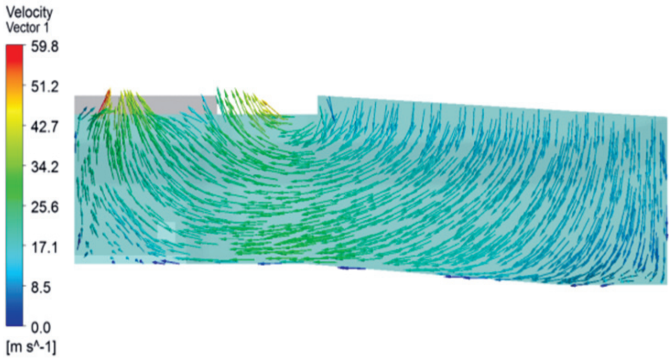

Figure 7. Vector plot – velocity (m/s).

pressure drop estimate accurately. Outlet louvers along with fan out area are modelled and are as shown in Fig. 8.

Fan outlet is simplified and louvers are placed above it. Distance between fan outlet and louver also defines the pressure drop characteristics across louvers. Results from CFD analysis are presented in following Figs. 9, 10, and 11, respectively.

Velocity magnitude was observed to be low in the region of fan hub diameter. Sensitivity study was performed to check the effect of louver profile, distance between the fan and outlet louvers. Arrangement of outlet louvers and fan was optimised based on these sensitivity study parameters.

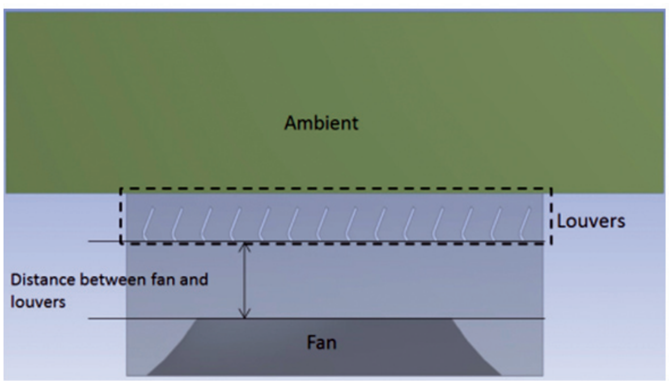

Figure 8. CFD domain - outlet louvers.

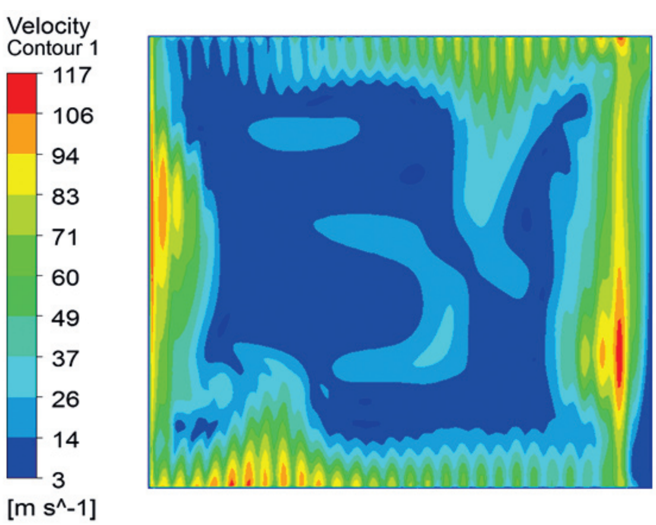

Figure 9. Contour plot – velocity (m/s) – after outlet louvers.

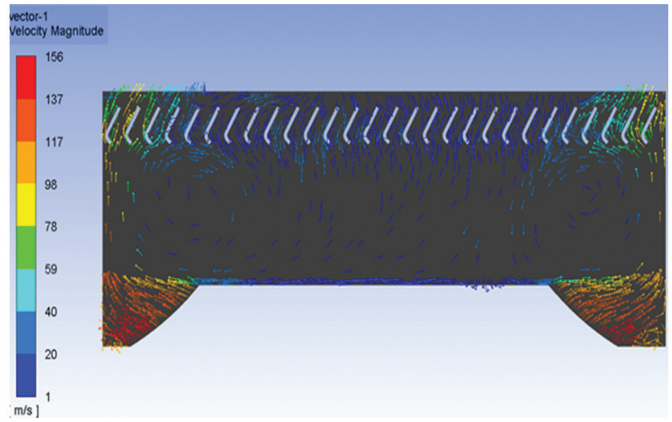

Figure 10. Vector plot – velocity (m/s).

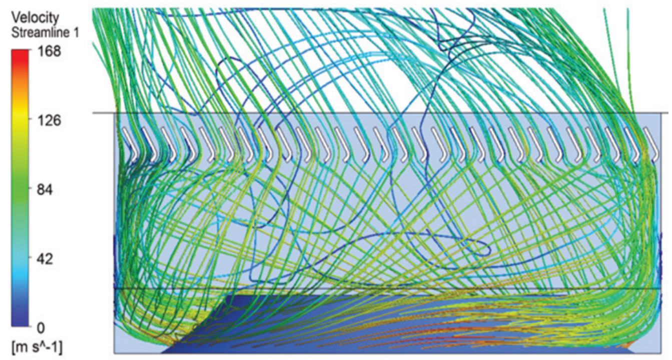

Figure 11. Pathlines – velocity m/s.

4.4 System Resistance

Total pressure drop is the summation of pressure loss across intake louvers, heat exchanger, air duct and outlet louvers. Estimated pressure loss data from analysis was added and system total pressure loss was assessed. System's total resistance was plotted against the fan curve to gauge the fan operating point as shown in Fig. 12. Based on operating point power required to drive the fan was calculated.

From this data, fan RPM was finalised and hydraulic circuit was designed to deliver the rated RPM for the fan. Furthermore this data forms the basis to control the fan RPM based on flow required and temperature of the coolant. Additional margin available on pressure side can be gauged from this graph.

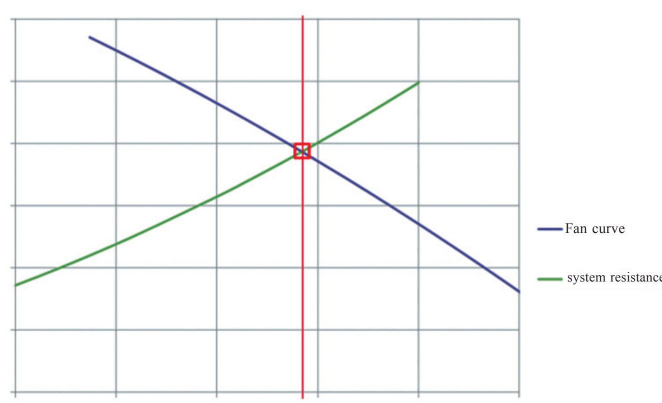

Figure 12. System resistance curve.

5. SYSTEM INTEGRATION

All aggregates viz. engine, transmission, all radiators, fan, duct, air filtration system and associated hydraulics were integrated to form a complete powerpack.

6. CONTROL AND INSTRUMENTATION

In order to continuously monitor the thermal data of powerpack, temperature sensors were placed at various locations in the powerpack. They were placed mainly on 'in' and 'out' side of heat exchangers. To monitor the temperature of cooling air, additional sensors were mounted inside the air duct. For optimising fan power, fan controller was incorporated to govern the fan RPM depending on the coolant and charged air temperatures.

7. FACTORY ACCEPTANCE TEST AND FIELD TRIALS

After completion of cooling system integration and instrumentation, air flow measurement was done in-house. For measuring the air flow through heat exchangers, area over the heat exchangers was divided into grids. Hand held digital anemometer was used to measure the flow velocity at centroid of various pre-defined grid points. With this, average flow rate through heat exchangers was obtained. The air recirculation in the duct is avoided by the appropriate baffle plates and sealing between the powerpack and the top cover of the hull. Subsequently vehicle was fielded for desert trials. Similar instrumentation was incorporated in the desert trials. All the thermal data and the raw data obtained from the vehicle control units were logged and processed for analytical purpose to ascertain the powerpack performance.

Temperatures at inlet and outlet of hot side of all heat exchangers were logged. Heat rejection on hot side was derived based on temperature difference across heat exchangers and engine RPM. This derived data of hot side heat rejection with time history was plotted. Figure 13 shows a sample data for the entire duration of test cycle.

On cold side of heat exchangers temperature of air has been monitored and logged. Depending on temperature difference between ambient and hot air coming out from heat exchangers, mass flow rate of air was estimated based on heat balance of hot side and cold side[2,3]. Figure 14 shows the temperature variation inside duct and compartment.

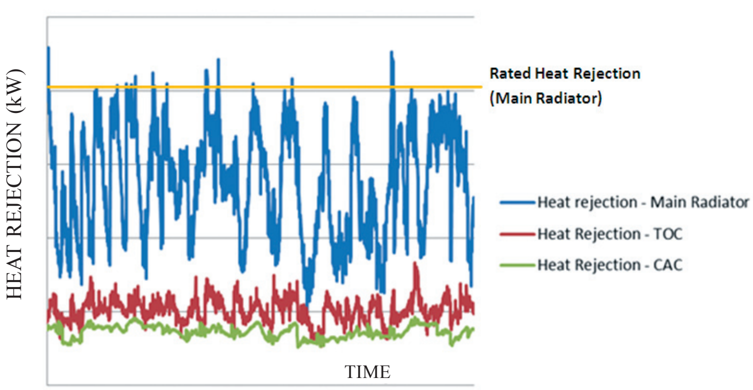

Figure 13. Heat rejection on hot side.

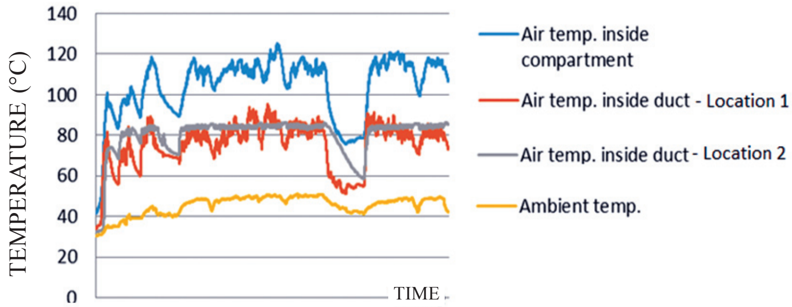

Figure 14. Air temperatures on cold side.

As discussed earlier, the temperature based fan control algorithm was developed and improvised as per real time data obtained during field trials.

8. CONCLUSIONS

After analysing the data from CFD analysis, it was evident that heat exchangers and outlet louvers are major contributors to the overall system resistance. Heat exchangers were sized optimally to cater specified heat rejection with reduction in airflow resistance. Since the louver profile has reservations due to ballistic prerequisites, the distance between fan and outlet louvers was optimised to reduce air flow resistance further. Overall system resistance was plotted against various fan models and a fan was selected for specified operating point. Flow measurement carried out during factory acceptance test was found to be in line with the anticipated fan operating point. The temperature based fan control algorithm optimised the fan performance and fed power to the fan on need basis thereby allocating the extra power for mobility.

The logged data obtained from the instrumentation and vehicle control units during desert trials, after processing, showed a good correlation between the analytical values and field data. Critical parameters viz. coolant and charged air temperatures were within their permissible limits. From this, it is evident that the overall performance of cooling system during field trials was consistent with the system requirements.

This approach of virtual prototyping followed by physical prototyping can be extended to design and optimise the cooling system for other tracked military vehicles, first time right.

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Mr Jayesh Namjoshi obtained Master's in Mechanical Engineering with specialisation in product development from Jonkoping University, Sweden in year 2008. He is currently Manager - Product and Technology Development Centre (Defence & Aerospace), L&T Limited. He is associated with Analytical and Experimental Techniques Group in the department. His main areas of interests are thermal management, optimisation and advanced analytical techniques for new product development.
His contribution in the current study is estimation of all flow parameters with the use of computational fluid dynamics furthermore analysing field data for thermal and flow parameters for validation.

Mr Sachin Wagle holds Mechanical Engineering Master's from Pune University in year 2005. He is Manager- Product and Technology Development Centre (Defence & Aerospace), L&T and is Technical Lead- Armored Systems which is a subgroup of guns, Missiles and armored systems BU. He is SAE member and his main interest areas are armored system, powertrain, suspension, reliability.
His contribution in the current study is components selection, architecture, design calculations, packaging of all aggregates entailing instrumentation for field trials.

Mr Murtuza Kundawala, obtained his Master's in Mechanical Design from IIT Bombay in 2009 and is currently DGM-Product and Technology Development Centre (Defence and Aerospace), L&T and heading the design group for guns and armored systems. His main areas of interest are armored systems, electro-optics, robotics and mechatronic systems.
His contribution in the current study is the powerpack assembly and integration, powerpack linkages with simulation, hydraulic circuit for fan drive system and torsional vibrations study.

Mr Manoj Srivastava, Post Graduate in Mechanical Engineering with specialisation in CAD-CAM from Gujarat University in year 2001, is currently DGM– PTDC (Defence and Aerospace), L&T and heading Advanced Analytical and Experimental Techniques Group. He is a member of Nuclear Society of India. His main areas of interests are shock and vibrations, hydrodynamics and propulsion system.
His contribution in the current study is sizing of heat exchangers, establishing the design parameters for heat exchangers and structural analysis for powerpack aggregates.