Performance Assessing of Natural vs Forced Ventilation in a Transformer Vault Using Computational Fluid Dynamics

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Abstract

Transformers are a key component and one of the more expensive pieces of equipment found in an underground utility distribution system.

Preventative maintenance is often overlooked because transformers can offer long-term robust service. Today’s need for non-linear loads and the addition of Distributed Generation (DG), reducing transformer age acceleration and providing transformer long term sustainability is a key consideration.

Generally, transformers are designed to function within their nameplate ratings. However, during loading times they are often loaded above their nameplate rating. Transformers in underground network and distribution environments are often overloaded by design for contingencies as a standard practice.

Transformers tend to generate large quantities of heat. The conversion of the energy inside the transformer is the reason for this heat. The heat generated varies with the load that is applied to the transformer. As transformer loads increase so does the heat generated, due to the windings and the associated core losses. This heat generation cannot be avoided and considerations must be given to methods to control, cool, and monitor thermal performances.

One of the main consequences of heat generation in transformers is accelerated insulation aging. As transformer insulation ages its insulating properties diminish leading to potential catastrophic failure. This is a public safety concern since any fault within the confines of the transformer can be catastrophic. These transformers are commonly located in underground vaults directly below pedestrian sidewalks with built-in natural convection grates that are traversed every day in major city centres.

These built-in grates give some natural convection cooling but are very limited in controlling the ambient temperature of the transformer environment. These grates are fully exposed and as such offer many disadvantages listed below:

- Exposure to roadside salts leading to equipment corrosion and failures
- Exposure to debris dropping down in the vault
- Exposure to contamination dumping by businesses or pedestrians
- Hazards of potential equipment failure exposure to walking pedestrians

The VaultVent™ is specially designed to address these concerns. The built-in exhaust fan helps maintain a more ideal ambient temperature while pulling heat away from the transformer. This design eliminates the need for exposed gratings, providing smart thermal control to extend transformer life and improve safety of surroundings.

I. Introduction

Compared to the testing facilities at the factory, a transformer runs hotter in underground vaults and the life expectancy reduces unexpectedly when the room temperature exceeds the permissible maximum temperature[1]. Therefore, the ventilation system must be designed correctly in a transformer vault. When the ambient air temperature is low, natural ventilation is generally sufficient. However, at higher temperatures, there is a danger that the allowable temperature for the equipment may be exceeded. In many situations, it is not possible to achieve allowable temperature for the equipment simply based on the natural ventilation and the design criteria are not fulfilled.

Transformers run hotter in underground vaults than they do in factory test environments. Life expectancy of the transformer is reduced when room temperature exceeds the maximum permissible ambient temperature [1]. Therefore, the ventilation system must be designed correctly in an underground transformer environment. When the ambient air temperature is low and load applied to the transformer is within limits, natural ventilation is generally sufficient. However, at higher temperatures and peak load conditions, there is a danger that the allowable ambient temperature for the equipment may be exceeded. In many situations, it is not possible to cool the underground vault environment sufficiently to achieve allowable temperature using natural ventilation. Therefore, forced ventilation should be used to ensure the temperature does not exceed the permissible maximum temperature.

The main objective of this white paper is to assess the performance of natural ventilation vs forced ventilation in a transformer vault using computational fluid dynamics (CFD). For this purpose, the velocity and temperature fields inside a vault, on the walls of the vault and transformer are studied qualitatively and quantitatively. In addition, convection and radiation heat fluxes on the walls are calculated and the main heat transfer mechanisms for natural and forced ventilation are explored.

II. Computational Methodology

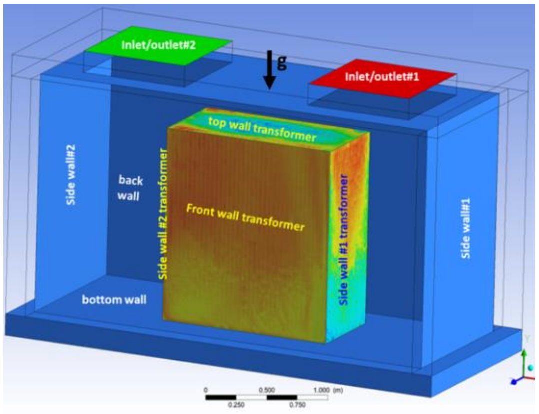
shows the computational domain and boundary conditions (BCs) for two scenarios of vault ventilation namely: natural and forced convection. For the natural ventilation scenario, the fluid flow can enter and exit the grates freely (inlet/outlet BC). While for the forced convection scenario, at the inlet the mass flow rate BC is applied, and pressure outlet BC is utilized at the outlet. Moreover, fixed value and couple boundary conditions are used on the external and internal walls of the vault respectively. The vault size considered for this analysis is in Table 1.

Table 1. Vault Details

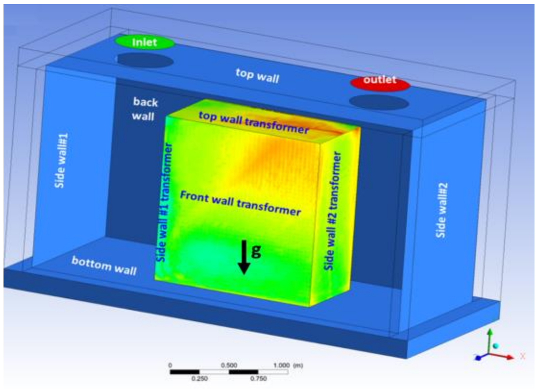
Description	Parameter
Underground vault size	11.5ft x 4.5ft x 6.5ft.
Transformer kVA (w/ mineral oil)	50kVA (55C rise)
Grates dimensions	Qty (2) – 24in x 24in
VaultVent opening	26in diameter

The governing equations for the conservation of mass, momentum and energy are based on Reynolds Averaged Navier Stokes equations. The realizable high-Reynolds $k-\varepsilon$ model[2] is utilized for turbulence modeling. The turbulent heat fluxes are modeled based on the simple gradient diffusion hypothesis where the turbulent flux is linked to the mean temperature gradient by analogy with molecular diffusion [3] and radiation is mode led by the discrete ordinate method [4]. All the transport equations (momentum, energy, k and ε) are discretized using a second order upwind scheme. Pressure interpolation is of the second order. The SIMPLE algorithm [5] is used for pressure-velocity coupling. Convergence is assumed to be obtained when the scaled residuals reach 10^{-6} for all equations

Figure 1 – Computational domain boundary conditions for two cases: Natural and Forced Convection



a) Scenario 1: Natural convection ventilation



b) Scenario 2: Force convection ventilation

Table 2. Boundary Condition Details

	Natural ventilation
Inlet	Inlet/outlet
Outlet	Inlet/outlet
External walls of the vault	Fixed value for T & No slip
Internal walls of the vault	No slip Coupled (solid/fluid interface) Emissivity (ε_i) = 0.94
Walls of the transformer	No slip Coupled (solid/fluid interface) Emissivity (ε_e) = 0.85
Transformer [W]	3740

	Forced ventilation
Inlet	Mass flow rate @ T=303K
Outlet	Pressure outlet @ T=303K
External walls of the vault	Fixed value for T & No slip
Internal walls of the vault	No slip Coupled (solid/fluid interface) Emissivity (ε_i) = 0.94
Walls of the transformer	No slip Coupled (solid/fluid interface) Emissivity (ε_e) = 0.85
Transformer [W]	3740

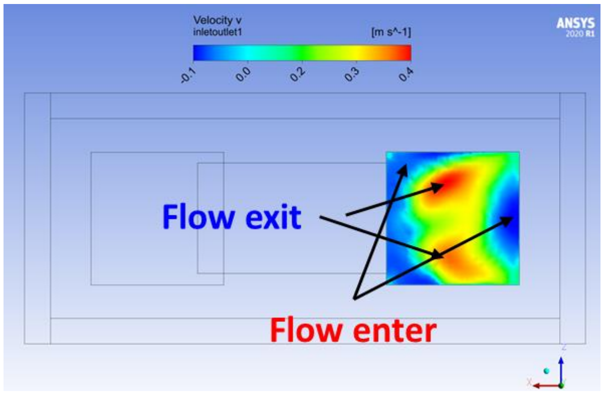
III. Discussion of Results

Flow and heat transfer for natural ventilation scenario

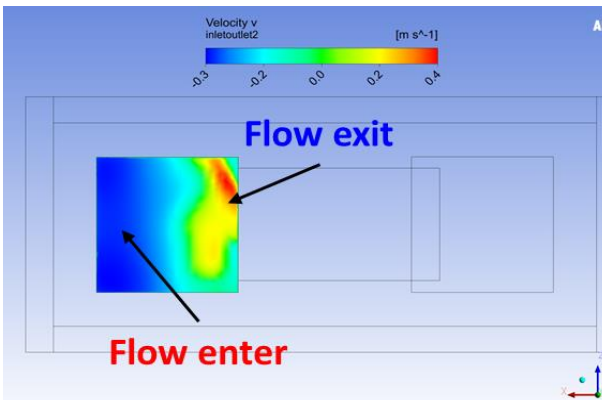
The distribution of vertical velocity in **Figure 2** (a-b) at the inlet/outlets 1 and 2 indicates that the fluid flow can enter (negative value-blue color) and exit (positive values-red color) to the vault freely. The maximum flow rate is 0.15 kg/s for both grates and the maximum local value of velocity is less than 0.4 m/s. Moreover, **Figure 2** (c-d) shows the leaving of hot air (red color) from the vault and the entering of fresh air (blue color) into the vault.

As it can be seen the minimum value of instantaneous temperature is 303K (29.9°C) which is the ambient temperature, and the local maximum value of instantaneous temperature is 314K (40.9°C) in this scenario. The area-weighted average of temperatures at inlet/outlets 1 and 2 are 308.15K (35°C) and 304.77K (31.6°C) respectively which are lower than the local values.

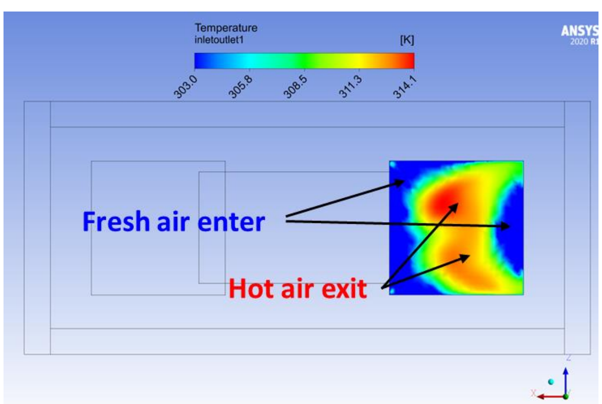
Figure 2 - Distribution of vertical velocity and temperature at the inlet/outlet 1 and 2 when the ventilation is achieved by natural convection (Scenario 1)



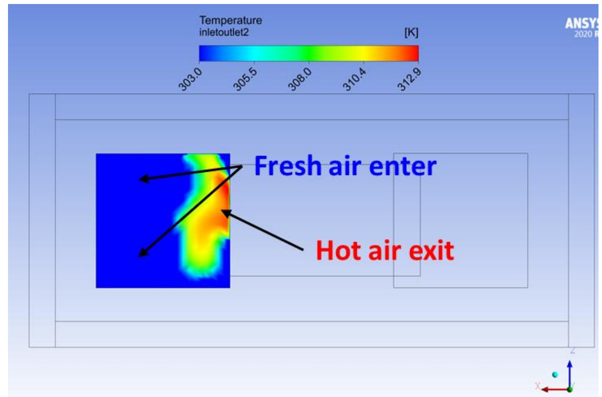
a) Vertical velocity at inlet/outlet 1(top view)



b) Vertical velocity at inlet/outlet 2 (top view)



c) Temperature at inlet/outlet 1 (top view)



d) Temperature at inlet/outlet 2 (top view)

Figure 3 shows the complex flow field (vortical structures and reverse flows) inside the vault. In this scenario, flow behaviour is completely controlled by buoyancy (buoyancy-driven flow). In other words, the leaving/entering of hot/fresh air from/to the vault is induced by the body force resulting from gravity and density gradient.

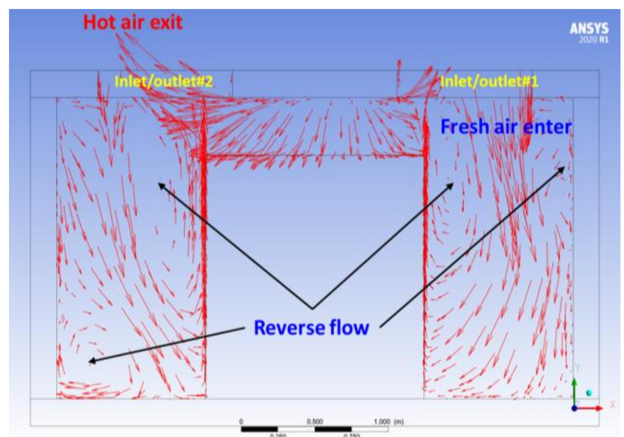


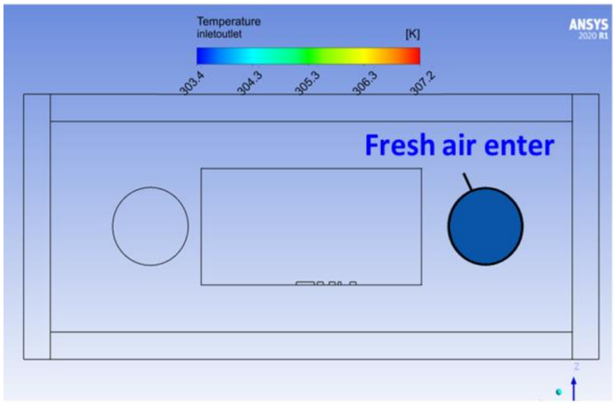
Figure 3 - Velocity vectors at the z=0 plane which is in the middle of the vault; ventilation is achieved by natural convection (scenario 1)

Flow and heat transfer for forced ventilation scenario

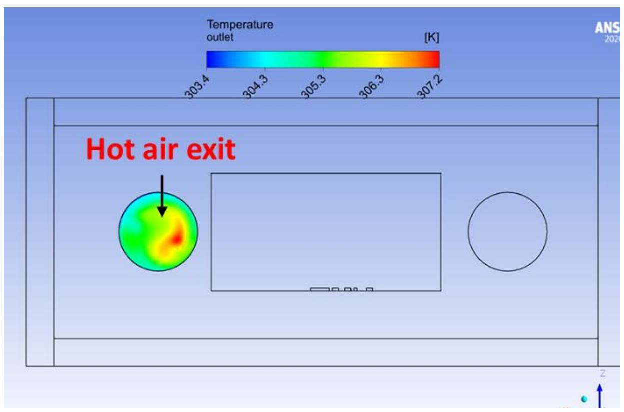
This section shows heat transfer and fluid flow characteristics of scenario 2 where a fan is used for enhancing ventilation on the walls of the transformer and vault.

Figure 4 shows the distribution of temperature at the inlet and outlet of the vault. The minimum value at the inlet is 303K (29.9°C) which is the ambient temperature. The local maximum and average values of temperature at the exit is 307K (33.9°C) and 305.5K (32.4°C) which is 7K (°C) and 8.5K (°C) less than that in scenario 1 respectively.

Figure 4 - Distribution of temperature at the inlet and outlet when the ventilation is achieved by forced convection



a) Contour of Temperature at the inlet (top view

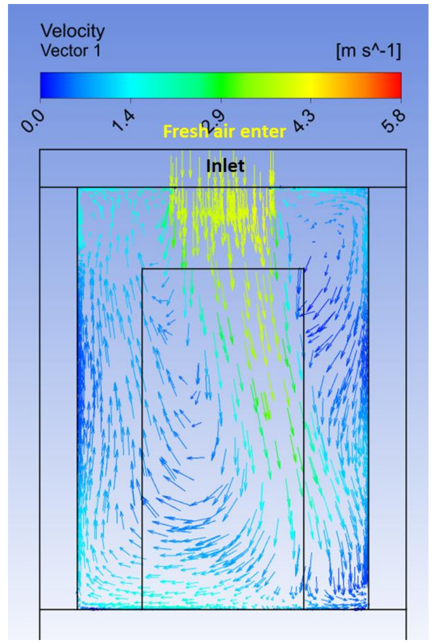


b) Contour of Temperature at the outlet (top view)

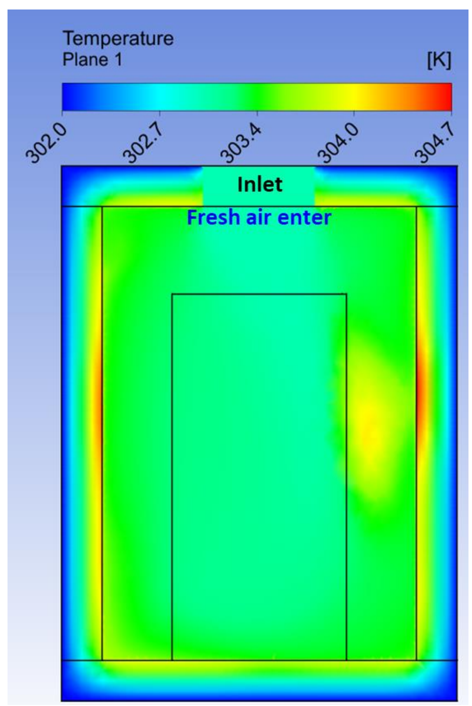
The leaving of hot air from the vault and the entering of high momentum fresh air into it is shown in **Figure 5**. The complex flow field inside the vault when the fan is used for ventilation is obvious. In this case, flow behaviour is controlled by the high-speed velocity field induced by the fan.

Figure 5 (a-b) shows that the temperature distribution at the inlet section of the vault is less than that at the exit section because the fresh air is drawn into the vault from this side. **Figure 5** shows that the magnitude of maximum velocity is less than 5.8 m/s for this scenario which is more than ten times larger than scenario 1. Additionally, the maximum local temperature inside the vault at the exit section is nearly 309K (35.9°C) which is 9K (°C) lower than that in the same section for scenario 1.

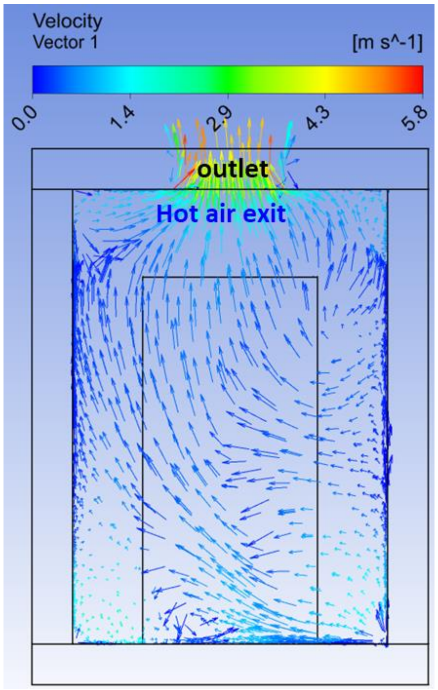
Figure 5 - Side view representation of flow and temperature fields at the inlet and exit planes for scenario 2 when the ventilation is achieved by forced convection



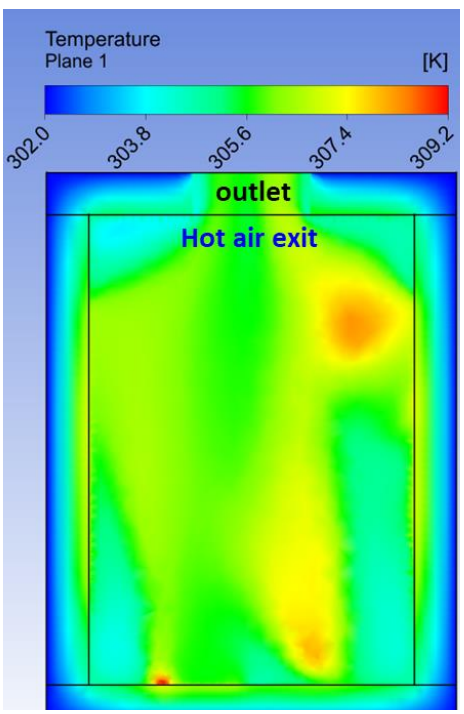
a) Velocity vectors at the inlet plane section



b) Temperature contour at the inlet plane section



c) Velocity vectors at the exit plane section



d) Temperature contour at the exit plane section

Comparison of thermal characteristics for natural and forced ventilation

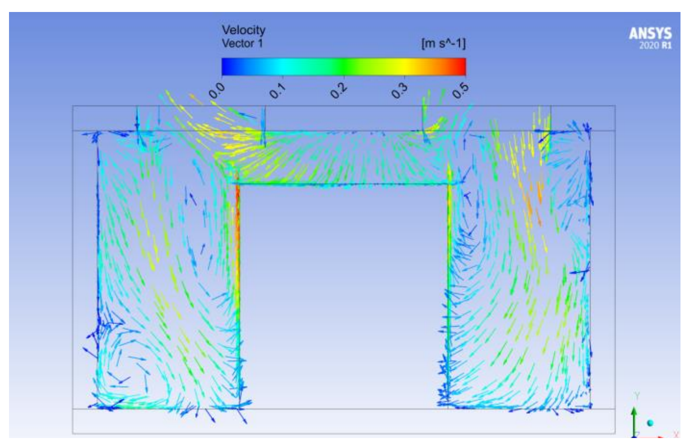
Table 3 shows that the mass flow rate has been increased from 0.15 kg/s in scenario 1 to 0.94 kg/s in scenario 2. It means that the local flow velocity for scenario 2 is more than ten times larger than scenario 1 (see **Figure 6**). Moreover, a comparison of the average temperature of hot air at the exit of the vault for scenarios 1 and 2 indicates that in scenario 2, the average temperature has been reduced from 314K (40.9°C) to 305.5K (32.4°C) confirming the improvement of heat transfer for the force ventilation in scenario 2.

Table 3. Comparison of temperature and mass flow rate at the inlet and out of natural (scenario1) and forced (scenario 2) ventilation

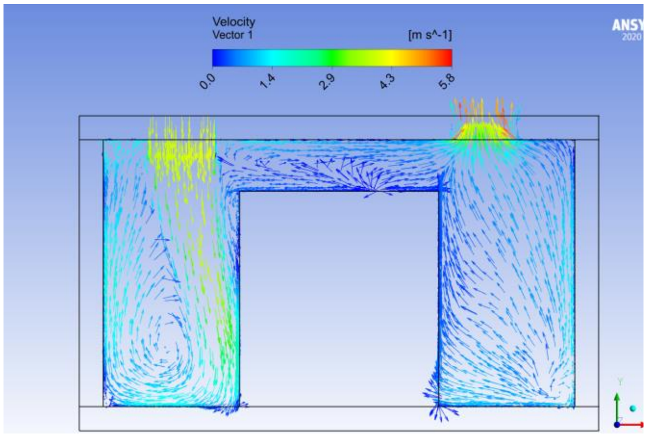
Scenario	Patch	*Max Temp	Avg Temp	Mass Flow Rate
#1	Inlet/Outlet1	314.1	308.15	0.15
	Inlet/Outlet2	312.9	304.77	0.15
#2	Inlet	303	303	0.94
	Outlet	307.22	305.49	0.94

Note – Since in scenario 1 the flow can exit and enter the vault freely, for each inlet/outlet, average temperature and max temperature are very different

Figure 6 Velocity vector at the z=0 plane which is in the middle of the vault (front view)



a) Natural ventilation (Scenario 1)



b) Forced ventilation (Scenario 2)

Figure 7 (a,b,c) and **Figure 7** (d,e,f) show the magnitude of average temperature and heat fluxes on the walls of the transformer and vault respectively. **Figure 7** (a) indicates that the walls of the vault are mainly cooled by convection; they receive heat from the transformer by radiation and cool by convection. It is obvious that the average temperature on the different walls of the vault has been reduced in scenario 2. The hottest wall is the top wall and the coldest walls are the sidewalls.

The magnitude of wall temperature of the transformer and the vaults in **Figure 7** (a,d) shows that when forced ventilation is used the average temperature on the different walls is reduced by at least 3.5K (°C) and 2.2K (°C) respectively compared to scenario 1(except for the bottom wall, where the heat transfer is controlled by pure conduction). Moreover, results indicate that when force ventilation is employed, the average temperature difference on the walls of transformer (based on the difference of temperature on all the walls of transformer) is reduced 46.2K (°C).

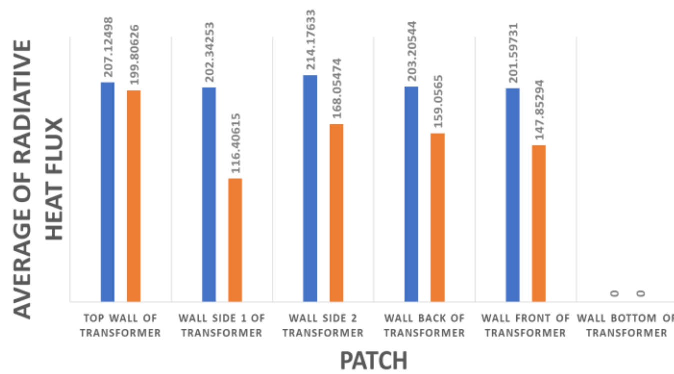
Figure 7 shows that the heat transfer mechanism for cooling the transformer is different for scenarios 1 and 2. Bar charts in **Figure 7** (b-c) indicates that in scenario 1 the walls of the transformer are mainly cooled by radiation. While for scenario 2 they are cooled mostly by forced convection. It should be emphasized that the model was designed using the worst-case scenario of having the bottom wall of the transformer placed on the bottom wall of the vault (floor) without any space. Therefore, the radiation heat flux is zero on this wall and is cooled by conduction of solid/solid. Most transformers have varying degrees of space depending on the application.

The comparison of the average temperature and heat fluxes in scenarios 1 and 2 in **Figure 7** demonstrates that forced ventilation is an efficient way for heat transfer improvement in a vault to reduce the temperature of the transformer and the walls of the vault.

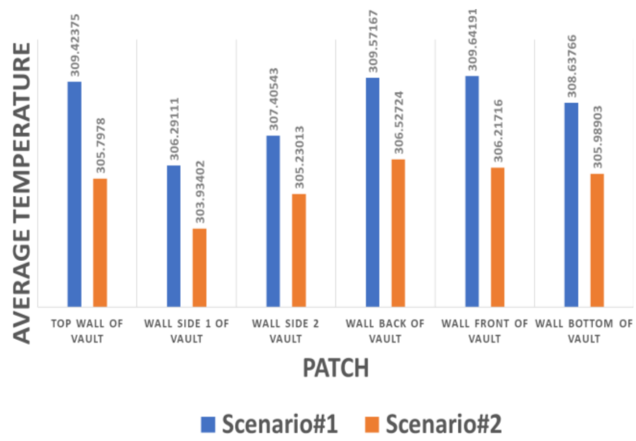
Figure 7 – Comparison of thermal characteristics on different walls of the transformer (a,b,c) and vault (d,e,f) for scenarios 1 & 2 when ventilation is achieved by natural and forced convection respectively

a) Comparison of temperature on different walls of the transformer for Scenarios 1 & 2

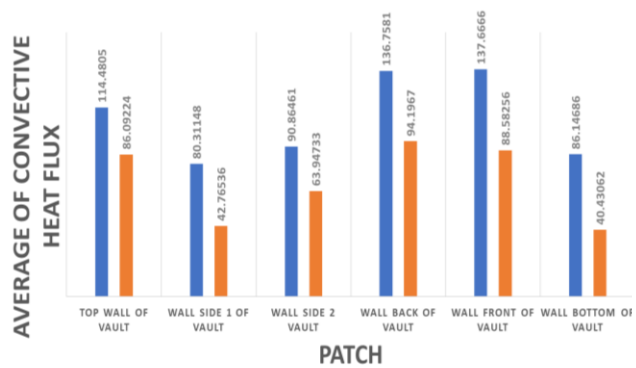
b) Comparison of convective heat flux on different walls of the transformer for scenarios 1 & 2



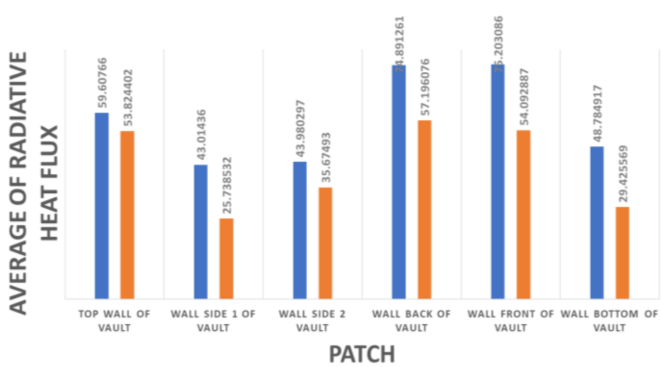
c) Comparison of radiative heat flux on different walls of the transformer for scenarios 1 & 2



d) Comparison of temperature on different walls of vault for scenarios 1 & 2



e) Comparison of convective heat flux on different walls of vault for scenarios 1 & 2



f) Comparison of radiative heat flux on different walls of vault for scenarios 1 & 2

IV. Conclusions

CFD simulations indicate that with forced ventilation the heat transfer inside the vaults will be enhanced and the transformer becomes cooler in comparison to natural ventilation demonstrated in scenario 1.

Results indicated that by increasing the velocity of fluid flow in the vaults the dominated heat transfer mechanism is changed from radiation in scenario 1 to forced convection in scenario 2. The comparison of convective and radiative heat fluxes shows that in the natural ventilation case the transformer is cooled mostly by radiation, while in forced ventilation in scenario 2 the convection heat transfer is more than radiation. Therefore, when there is a danger that the allowable temperature for the transformer is exceeded the permissible maximum temperature, forced ventilation should be utilized in the design.

IEEE C57.91-2011[6] is the guide for loading of mineral-oil-immersed transformers. Per this standard, the minimum normal transformer insulation life expectancy is 180,000 hours (20.5 years). The rated hot spot temperature (HST) common for transformer insulation is 110°C. Operating transformers above rated HST will accelerate insulation ageing exponentially. The HST is based on several factors particularly the ambient temperature, top oil temperature and transformer loading conditions.

IEEE C57.91-2011 details how to determine the insulation percent loss of life. We can do this by calculating the equivalent hours of life consumed as a function of time at a given temperature considering there is ideal insulating oil integrity. Assuming a daily 110% overload factor during 4 hours of evening peak time (130°C HST) can result in a reduction of insulation life by 6.25 years (30% decrease). Based on data detailed in Section 7a, the average drop in surface temperature for the subgrade transformer is 46.2°C. Force vault ventilation will contribute significantly to dropping the surface and ambient temperature during peak load times. Forced ventilation has a direct impact on the HST of the transformer which can potentially add back 4.25 years or more of equipment operating life.

V. References

1. Lockie, A.M. and D.K. Whirlow, *Thermal Performance of Distribution Transformers in Underground Vaults: I - The Problem.* IEEE Transactions on Power Apparatus and Systems, 1968. PAS-87(9): p. 1741-1745.
2. Shih, T.H., et al., *A new k-e Eddy-viscosity model for high Reynolds number turbulent flows-model development and validation.* Comput. Fluids, 1995(24): p. 227–238.
3. Pope, S.B., *Turbulent flows*. 2000: Cambridge University Press.
4. Chui, E.H. and G.D. Raithby, *COMPUTATION OF RADIANT HEAT TRANSFER ON A NONORTHOGONAL MESH USING THE FINITE-VOLUME METHOD.* Numerical Heat Transfer, Part B: Fundamentals, 1993. 23(3): p. 269-288.
5. Versteeg, H.K. and W. Malalasekera, *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*. 2007: Pearson Education Limited.
6. IEEE, C57.91-2011, *Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators*