Flow and heat distribution analysis of different transformer sub-stations

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Abstract. This paper describes CFD investigation on the flow and heat transfer in transformers at different sub-station buildings. The analysis aimed to determine the cooling capability of the existing transformer building employing natural ventilation system to dissipate heat sufficiently when new dry-type transformer operating under full load condition is used. The transformer and building models were developed based on the actual transformer configuration in operation at three different locations in Malaysia. The calculation was carried out on three different types of sub-stations namely stand-alone, attach-to-building and underground. The effect of natural ventilation speed and building volume on the transformer surfaces temperature are also investigated. It was predicted that the existing sub-station configuration is able to dissipate heat produced from the dry type transformer by using its natural ventilation system regardless of the sub-station types. However, the smallest building case shows relatively high surrounding temperature.

1. Introduction
Currently the majority of all distribution transformers in Malaysia were of the oil-cooled type at which cooling of the transformers are provided by liquid oil and in some cases gas. The use of oil-cooled transformer has proven to be effective in helping to ensure that the transformer surface temperature does not exceed the safe temperature limit of any particular transformer. Nevertheless, the oil-cooled transformer poses several disadvantages such that it needs to be maintained frequently and the need for cooling oil-handling facility that requires higher maintenance costs. With the advent of oil-free transformer, the maintenance of transformer could be made minimal and most importantly, the maintenance cost could be significantly reduced e.g. cast resin transformer. However, it is known that the dry type transformer dissipates large amount of heat as compared to the oil-cooled one. The cooling of the dry-type transformer thus depends solely on the natural ventilation system or forced cooling using different medium such as air. Using this method, air has to be blown, usually from the bottom of the transformer in order to increase the rate of cooling of the transformer. One of the most important factor that need to be taken into account when replacing transformer of different characteristics is the ability of the existing sub-station (SS) to dissipate heat effectively when new transformer is installed.

Studies on transformer development are abundant in the open literature. The majority of these works emphasized on the detail cooling of the transformer windings [1-5]. Very limited works were given to the investigation of the cooling system for efficient heat dissipation in room containing the
transformer [6]. Thus this paper aims to qualitatively investigate the ability of the existing SS to dissipate heat resulted from the replacement of traditional oil-cooled to dry-type transformer. The work focused on three different type of SS commonly found in Malaysia and the detail of the SS model is explained in the following section.

2. Sub-station model descriptions

The SS models were developed based on the full scale stations located in Malaysia. Three different types of sub-stations were tested and the description of each case is shown in table 1. Different sub-stations (SS) have different building sizes and experience different air circulation. Figure 1 shows the stand-alone SS model which has an approximate dimension of 8m×4m×3m. This is the largest SS under investigation and there are 2 transformers with rating of 1000 kV. Figure 2 shows the model of an underground-type SS which dimension is slightly smaller than the stand-alone type SS. Its dimension is approximately 6m×3m×2.5m and this SS is located at underground car park close to the vehicle entrance area. The last SS model was based on compact/attached-to-building type which dimension is the smallest among all the three SS. The dimension is approximately 4m×3.5m×2.5m and the transformer placed in this building is a single core with multiple cylindrical surface areas. This is shown in figure 3. For Case 3, detail model was developed where air and window louvers were also taken into account. The amount of air entering the SS will be calculated based on the inlet boundary conditions imposed at one end of the SS. This is a more realistic scenario whereby the volume of air entering the SS is calculated based on the pressure difference between the inside and outside of building.

Table 1. Case descriptions

| Case  | Descriptions                  |
|-------|-------------------------------|
| Top   | Stand-alone SS                |
| Bottom| Underground SS                |
| Left  | Compact/Attach-to-building SS |

Figure 1. Stand-alone SS
The flow inside the sub-station is fully turbulence despite the relatively weak flow as air passes through door and window louvres from the surrounding environment. The mathematical equations describing steady, flow can be casted into general form as follows:

\[
\frac{\partial (\rho \mu \phi)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) + S_\phi
\]

where \( \phi \) is the three momentum components, \( \Gamma_\phi \) is the diffusion coefficient of the transported variable \( \phi \) and \( S_\phi \) is the source term. For mass conservation equation, the variable \( \phi \) is set to unity and thus the right hand side of the equation is zero. The introduction of turbulence into the Navier-Stokes equation resulted in extra terms that require additional equations for closure. In order to close the equations, the standard \( k-\epsilon \) turbulence model is used to model the turbulence fluctuations (Lauder and Spalding, 1972; Launder and Spalding, 1974). The two-equation models consists of one differential
transport equation for the turbulence kinetic energy, \( k \) and one for its dissipation rate, \( \varepsilon \) and is given by the following equations:

\[
\frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \rho (P_k - \varepsilon) \tag{2}
\]

\[
\frac{\partial (\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + S_\varepsilon \tag{3}
\]

Where \( \mu_t \) is the eddy viscosity and is computed from:

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}
\]

where \( C_\mu \) is the turbulence constant. In this work, SIMPLE calculation algorithm is used for the coupling of continuity and momentum equations. The numerical equations are solved using finite volume solver, FLUENT which is able to handle different types of structured, unstructured and hybrid grids.

4. Mesh generation and boundary conditions

Generating a good mesh is extremely important in CFD in order to accurately predict the flow and heat transfer characteristics in complex geometry. In this study, a combination of structured and unstructured grid was applied to all models. Figure 4(a) to 4(c) illustrates the mesh scheme applied to all SS geometries. Higher mesh concentration was applied to critical regions and in this work, near the transformer surface and volume for resolving the conjugate heat transfer due to conduction and convection. The number of cells generated for Case 1, Case 2 and Case 3 are 1 445 298, 762 823 and 444 771 respectively. This is sufficient to resolve the flow field and grid dependency study has revealed that the current mesh is sufficient to accurately predict the flow and heat transfer characteristics inside the flow domain.

To accurately emulate the existing natural ventilation flow inside the SS, air flow measurement was taken on-site and the value obtained was imposed as the boundary condition for the computational simulation. In order to compare the heat dissipation ability for different SS, the transformer load is assumed to be identical for all cases. In this case, different loads are tested and in the range of 2.7 kW to 10.8 kW, representing 25% to 100% actual load. In reality, the transformers are operated at lower load depending on the demand requirement surrounding the area. The geometrical model of the transformers were simplified where array of fins for heat transfer enhancement were omitted and combined into a single block for each case. The effect of heat transfer enhancement was recalculated by increasing the heat transfer constant on the transformer surface.

5. Results and discussions

In general, very weak flow was predicted in all cases since the only driving force for the flow was due to natural air flow into the sub-station building. Despite the weak flow condition, the prediction of transformer surface temperature show acceptable temperature magnitude. This is extremely important to ensure that the surface temperature to be below the acceptable limit. Despite various security measures taken at each SS such as fire alarm and automatic sprinkler system, prior knowledge in estimating the maximum temperature of transformer surface temperature is vital. Figure 5 shows the variation of average transformer surface temperature against transformer load. Comparison is made between two transformers place at different locations within the same SS. In this case, transformer #1 is placed near to the corner while transformer #2 is placed next to transformer #1 towards the SS centre. The average surface temperature was higher for transformer #1 and this could be attributed to
the lack of air ventilation penetration since transformer #1 is located at the SS corner. Thus, the heat dissipation for this transformer is less as compared to transformer #2. This trend is applied regardless of the transformer load. It could also be observed that at higher load, the temperature difference between the two transformers is higher. It is predicted that at full load condition, the maximum average transformer surface temperature is approximately 71ºC and 74ºC for transformer#2 and transformer#3 respectively.

![Mesh scheme for all SS models](image)

**Figure 4.** Mesh scheme for all SS models

The average transformer surface temperature for Case 2 is illustrated in figure 6. For Case 2, the average air speed entering the SS is slightly higher as compared to Case 1 and thus heat dissipation is more pronounced. The predicted transformer surface temperature is approximately 69ºC. Another factor that might contribute to the lower transformer surface temperature in Case 2 is due to the fact that the SS only contains single transformer thus, the total heat needs to be dissipated by ventilating air is less compared to Case 1. Figure 7 shows the temperature profiles of transformer against the load for Case 3. The SS was the smallest among all the stations under investigation and thus, heat dissipation is not as good as in Case #1 and #2. The lack of ventilation air entering the critical regions within the SS causes inefficient heat dissipation on transformer surface. In addition, due to the smaller SS size, the rate of heat accumulated is greater than the heat dissipation for this SS. This results in higher surface temperature at full load condition with a magnitude of 80ºC. Nevertheless the temperature is within an acceptable range. The measured local air temperature just above the top transformer surface at 25% load condition show good agreement with the predicted one.
6. Conclusions
The CFD calculation of flow and heat transfer in different SS models has been carried out. Emphasis is given to the prediction of transformer surface temperature when only natural ventilation air was present inside the building. Based on the prediction, the following conclusions can be withdrawn:

- The flow inside the different stations was very weak due to the slow naturally circulating air. Despite the low velocity air, the heat could be dissipated effectively due to reasonably large volume air change in each station.
- The transformer location inside a sub-station plays an important role in determining the surface temperature. Transformer located away from the ventilating air path has higher temperature as compared to the one located at the air flow path. The average transformer surface temperature in all stations increases almost linearly with the transformer load.
The prediction of transformer surface temperature in all stations show acceptable temperature magnitude at full load conditions. Thus, the existing natural ventilation system in the stations under investigation was able to dissipate heat when the oil-cooled transformer was replaced by the dry-type.

**Figure 7.** Average transformer surface temperature (Case 3)

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