ENVIRONMENTAL IMPACT on TRANSFORMER THERMAL PERFORMANCE

ABSTRACT

There is limited information in open literature on environmental conditions effecting thermal performance of substation equipment. Majority of the information about transformer thermal performance is concentrated around heating of its parts due to internal sources. It appears that cooling medium (water and (or) surrounding air) temperature and atmospheric pressure, interpreted as installation's altitude, are the only external factors impacting on transformer thermal performance.

The paper is an attempt to clarify the effects of some other environmental elements. Comparison of different environmental conditions has been presented in terms of how it is affecting temperatures of different parts of the equipment. Some examples of in-service conditions have been presented. Finally, conclusions and recommendations have been derived based on the findings.

Introduction

Transformer can be classified using a concept of the thermodynamic system. Using principals of thermodynamics big range of design concepts is divided into two types of the systems:

sealed unit is a closed system

The design allows doing expansion-contraction work of a membrane or its flexible walls; some allow to increase its headspace pressure. Of course, definition of closed system is idealistic, means designers target is to make transformer with no leakage and absorption from surroundings. Quality designed and build transformer has negligible mass transfer and we can assume that sealed designs are closed thermodynamic systems.

Dr. Yuriy Odarenko

Design Development Engineer, Wilson Transformer Company

free breathing unit is an open system

This design concept allows for exchange of some matter though free breathing system. As the transformer internals has the same ability to expand and contract as sealed units, the work make a controlled exchange between gaseous headspace and environment. There should be minimized moisture and solid particle intake from atmosphere during the process.

Both thermodynamic systems have one characteristic in common. It is thermal energy exchange. Either system is designed to dissipate heat. The energy is dissipated to the environment that has a certain capacity to absorb. Most common absorption media is surrounding gas (air cooled design) or continuum liquid flow (water cooled design) that is in contact with the surface of transformer cooling system. Transformer standards and guides give elaborative information about two thermodynamic parameters of the surroundings:

- *temperature*

It is the parameter of the cooling media potential energy and is related to both gaseous and liquid matters.

- *pressure*

Density of gaseous matter and other thermodynamic parameters (kinematics viscosity, thermal conductivity and specific heat) depend on pressure. In our case it is surrounding air. The parameter is expressed in altitude measures in respect to sea level as air pressure is mainly depend on altitude.

However, is the list of surrounding effects and their parameters, that significantly affect the heat dissipation process, complete? Who significant can be other affects on heat dissipation from transformer? Is it possible to reduce harmful impact of the environment and to increase positive influence of the surroundings? The paper is an attempt to highlight some important facts around the topic.

Some of the surrounding conditions that had potential to impact on heat dissipation process are identified below:

- natural conditions:
  - wind
  - rain
  - dust
  - solar radiation
  - natural landscape
  - humidity
- built conditions:
  - transformer external layout
  - build environment (fire walls, sheds, buildings, any abstractions and enclosures, etc.)
- and some combinations of the above parameters.

Relevant transformer standards and guides provide no information related to the above factors and their impact on thermal performance. While exploring the environmental standards it was found that most of the information classify different levels of harshness of particular environmental affect which may adversely impact on an equipment safe and reliable operation, and long term service life [1-5]. Some standards specify test procedures related to particular factor of surroundings [6-11] but do not distinguish their impact on thermal performance. Only solar radiation is directly related to the thermal performance of a equipment [10, 11]. In the AS 60068.2.5 and AS 60068.2.9 standards impact of solar radiation on the object of interest is identified by means of physical testing.

There is an extensive research done in studding of the environmental affects on buildings [12- 17]. Some of them study indirectly [12-14] or directly [15-17] particular environmental conditions on heat dissipation efficiency.

Natural landscape and build environment can be combined because their impact on heat dissipation does not distinguish how they have been formed. As it can be seen in the contest of

the article the build and natural obstructions and enclosures contribute as combined impact with one of the other natural environmental factors.

While exploring possibility of the different calculation methods for the environmental impacts it was found that CFD modeling can be implemented to assess impact of all mentioned above environmental factors on thermal performance of the substation equipment and in particular transformers. Some of the best CFD capabilities of ANSYS software have been used to study the above ambient conditions. Finite element method has been used for the models discretisation. All the models employ solving the base of the CFD modeling - Navie-Stokes equation, continuity equation and thermal energy equation.

Effect of each environmental factor on heat dissipation at the particular condition has been compared with a heat dissipation of a base condition. The base condition can be when either the studied factor is absent or when it is an average value. In order to estimate the affect of the surrounding factor(-s) in the article a heat dissipation efficiency (HDE) has been used and can be estimated as following:

$$HDE_{affect} = \frac{DE_{affect} - DE_{standard}}{DE_{standard}} \times 100\%,$$

where DE_{affect} is the heat dissipation (HD) of the studied environmental impact level in Watt,
$DE_{standard}$ is the heat dissipation of a standard condition in Watt.

Wind

Wind is a random dynamic phenomenon in space and time. Wind speed can be interpreted as a superimposed combination of constant value and random gusts in form of fluctuations.

Wind speed mean value increases with height above the ground. There is no obvious correlation between the wind oscillations at the different heights, the waveforms do not repeat, and the wind speed at any time can be described statistically but not predicted exactly.
The dominant frequency of wind gusts is between 0.01 Hz and 0.1 Hz according to Boggs and Dragovich [14]. There is no doubt that wind has some positive impact on heat dissipation from the heated matter when blowing directly on it.

If wind blows directly on transformer surface (transformer tank and its radiators) it creates forced convective heat transfer condition that can be described by the following criteria equation:

$$Nu = A \times Re^b \times Pr^c,$$

where *Nu* is Nusselt number, *Re* is a Reynolds Number, *Pr* is Pradtl number and *A, b, c* are the coefficients that are significantly impacted by the particular built environment, wind speed and direction for certain transformer external layout.

But what if wind does not blow directly on the object? Transformers are often surrounded by wire walls, buildings and other obstructions. In the paper qualitative impact on heat dissipation is presented for the particular site and for the following limited number of wind parameters:

- mean air velocity
- wind direction

The wind model represent transformer bay in ambient with free surface boundary conditions of external air. Only radiator bank is used because in the case it is the main heat dissipating surface.

In Table 1 HDE's at low, average and high wind speed and two wind directions are presented in respect to calm condition at the site. First wind direction is from east, second one is from west. These are the only wind air flow scenarios for the particular site build environment, the transformer general arrangement and yearly average wind rose data. It is mainly because the site is obstructed by the building from north that is several times bigger of the transformer enclosure. The results are compared to the calm whether at ONAN condition.

Table 1. HDE of wind for the transformer surrounded by certain obstruction.

Wind Speed	HDE_{wind}, %	
	easterly wind	**westerly wind**
high	**23.35**	**9.62**
medium	**-4.11**	**-22.11**
low	**-10.67**	**-28.66**

As you can see there is a possibility to have a negative affect of wind on HDE for the particular site build environment. It can happen because forced air flow can create recirculation zone in the transformer bay for some period of time which acts as a cavity. Air had been heated up in the cavity and had artificially increased ambient air temperature around the transformer.

Humidity

The effects of 10%, 50%, 100% humidity levels and supersaturated condition on heat transfer have been studied by simplified model. Supersaturated condition happens when there are condensed droplets suspended in the air. It is usually called mist or fog condition.
To solve the effect of humidity the species transport concept has been used with inbuilt water vapor relative saturation properties, latent heat effect of wet steam condition and evaporation- condensation droplets effects in the model. The model is representing radiator air duct with its inlet, outlet and radiator surfaces.
Effect of humidity level has been evaluated in respect to 50% humidity for different air velocity regimes. The results are presented in the Table 2.

Table 2.HDE of humidity for the simple radiator duct.

Humidity level	$HDE_{humidity}$, %			
	Air Natural Flow	**Low Wind Speed**	**Medium Wind Speed**	**High Wind Speed**
Medium intensity mist	11.26	**4.02**	**0.15**	**0.06**
100%	**0.00**	**0.07**	**0.07**	**0.08**
10%	**0.10**	**-0.05**	**-0.06**	**-0.05**

The significant change in heat dissipation is only visible for wet steam condition and for supersaturated condition of the ambient. It can happen either indoor or outdoor. When humid hot outdoor air suddenly cools while entering the building, for example, by means of air conditioning systems it can have some level of wet steam or even condensed droplets.

Rain

Rain model was studied on the simplified radiator model described in previous closure. The only difference in physical boundary conditions is that the water droplets representing the rain droplets had equivalent diameter range of 0.5-5 mm which is statistical range of the rain drop dimension.

There have been two precipitation rates modeled: first rate is between light and moderate (LMR) and second - between moderate and heavy (MHR). Droplets have been injected against and along air flow in the model to see the effect of the rain direction on heat dissipation. Air velocity varied from stagnant condition when there is no wind to the wind condition of 30 m/s in order to see combined effect of rain and wind on heat dissipation.

Rain is modeled as a dilute flow using Lagrangian approach which includes the following futures:

- modeling of the rain droplets include:
  - exchange momentum, mass, and energy between droplets and air with certain humidity level;
  - use of unsteady flow interaction;
  - drag force, pressure force, gravitation.
- rain droplets can deposit, slide and create film layer on the transformer surface, that:
  - interacts with air by means of momentum, heat and mass transfer;
  - interacts with transformer wall by means of momentum and heat transfer.

There is enabled evaporation and condensation effects on the surface of the droplets and water film layer that are interacting with water vapor of the air by means of saturation equation. Effect of HD by rain has been estimated based on HD without rain at the same air velocity. Results comparison is presented in the Table 3.

Based on the limited simulation results it can be stated that there is no significant variation in increase of heat dissipation due to rain by changing rain and wind direction, precipitation rate combined with wind speed. Bigger variety of condition has to be modeled to establish the correlation. But no doubt rain is a significant factor in increasing the cooling efficiency by 5- 15%.

Table 3.HDE of humidity for the simple radiator duct.

Rain Condition	HDE_{rain}, %		
	Air Natural Flow	**Medium wind speed**	**Maximum wind speed**
LMR	**7.07**	**10.75**	**3.98**
MHR	**12.91**	**13.31**	**10.32**

Dust

Some organic and inorganic dust particles are presented in Table 4 that can be present at site ambient.

Table 4. Dimensions of some organic and inorganic dust particles.

Particle	**Size, microns**
Beach Sand	100 - 10000
Fiberglass Insulation	1 - 1000
Grain Dusts	5 - 1000
Dust Mites	100 - 300
Saw Dust	30 - 600
Ground Limestone	10 - 1000
Cement Dust	3 - 100
Textile Dust	6 - 20
Combustion-related - motor vehicles, wood burning, open burning, industrial processes	up to 2.5
Fly Ash	1 - 1000
Milled Flour, Milled Corn	1 - 100
Coal Dust	1 - 100
Iron Dust	4 - 20
Smoke from Synthetic Materials	1 - 50
Lead Dust	2
Talcum Dust	0.5 - 50

Auto and Car Emission	1 - 150
Metallurgical Dust	0.1 - 1000

Dust particles deposited on transformer surface is a thermal insulation that is increasing transformer temperature rise. Figure 2 shows the affect. Ratio of deposited dust thickness to dust thermal conductivity is a parameter characterizing the “dust blanket”. Another parameter Kd is a ratio of contaminated surface to total external transformer surface. Transformer temperature rise for contaminated surfaces can be expressed with the following analytical equation:

$$\Delta t_{surf} = \frac{Q_{tot}}{A \text{ x } a + \sum_{i=1}^{n} \frac{K_d^i}{\frac{1}{a} + \Delta_d^i}}$$

where Q_{tot} is total transformer heat dissipation to the ambient in W, A is clean dissipating surface of the transformer in m, a is heat transfer coefficient (HTC) in w/m^{2}K, n is a number of dust layer thicknesses in case of the uneven thickness distribution.

The required result of the CFD simulation has to give the thickness distribution of the deposited particles on the transformer surface for the aim of estimation of its impact on reduction of cooling efficiency.

In the model linear distribution of the diameters of metallurgical dust particles have been chosen for the simulation of the site condition. Wind gusts from 5 to 30 m/s has been modeled. The source of particles has been located at both eastern and western sides at 45 m from the transformer bay.

Modeling of dust particles is using Lagrangian approach of a dilute flow same as for rain model but exclude mass transfer between particles and air and while particles are deposited on the wall they do not create continuum film layer but a dispersed deposition. The particles for a certain condition on the surface can resuspend from it. The result of the particle flow is shown on Figure 3.

Solar radiation

The solar radiation model geometry consists of transformer tank, HV bushing, radiators, site obstructions, that are blocking sun rays directed towards transformer surface, and air surrounding the bodies. There are assumptions been done for the solar radiation modeling in aim to get the affect without influences of other parameters. In the case air ambient temperature and PU loading has to be constant.

Physical aspects of the model are as following:

- CFD model consist of transient conjugate heat transfer between oil and air through transformer walls;
- real time solar radiation model creates an additional thermal loading on the transformer surfaces visible by sun beams.

The model computes traces of solar rays that include the following:

- collimated beams enter through semi-transparent walls in particular direction;
- ray-tracing algorithm calculate what nodes of the surface mesh are subjected to the incident radiation at certain angle for particular time of the day.

Solar rays energy dissipate completely on the nodes of the surfaces. Absorption, reflection, and scattering effects are not included in radiation model.

The algorithm performs a shading analysis on face-by-face basis to determine well-defined shadows on all faces. The ground reflectivity is used to compute the background diffuse radiation intensity component.

There are three conditions involved in transient behavior of the heat transfer: before appearance of the solar radiation load, during and after it disappear.

As described before the **first stage** is when inner bulk oil has highest thermal potential which is dissipating energy by, firstly, convective heat transfer on the inner surface of the wall in oil, secondly, by thermal conduction through the wall and, finally, by convection and radiation on the outer boundary to the ambient air.

When solar loading appear on outer surface it will take some time to heat the surface to the same level as the bulk oil. During the **second stage** heat dissipation through inner surface gradually reduces to zero. After that outer surface temperature will start to rise above corresponding bulk oil temperature and start transfer some heat to the oil. The level of the surface heat flux that heats up transformer oil from solar radiation will depend from the temperature difference of outer and inner surface of transformer wall. The process will continue until solar radiation will reach some negligible amount.

Third stage is transformer wall cooling process with the gradual heat flux reduction until the transformer surface will reach steady state. Steady state condition will be reached if time to reach steady state is less than the period of time without the solar loading. In practice it will be always the case.

As it can be seen on Figure 4 the outer surface of transformer has the maximum temperature increase due to solar radiation. It results in only marginal bulk oil temperature increase which is about seventeen times less then transformer outer surface temperature increase. Mean transformer oil temperature increases about sixty one times less then the outer surface that will marginally impact on winding temperature rise.

Site condition #1

First site environment is a typical mining, industrial or power plant surrounding with the coal combustion process as a source of energy. The one wire wall of transformer bay is in close proximity and along power plant building. Transformer bay is covered with a shed and has only one side without a wall. The bay opening is oriented to the east. As mentioned earlier, all the wind blowing at the configuration of the site will result in either western or eastern wind.

There are two possible harmful environmental condition identified for the existing site:

- certain wind speed and wind direction plus build obstruction that has been described in the chapter related to the wind (Figure 1);
- dust has been described in relevant chapter.

As general well-known rule ONAN cooling mode is designed for a range from no-load condition to a particular loading (0.5-0.7PU). Stagnant air condition is supposed to be the worst thermal condition and wind supposed to help in cooling the equipment. But it is not always the case. Wind can create recirculation zones. It artificially increases the ambient air temperature and reduces cooling efficiency. Simulated (Figure 5a) and actual (Figure 5b) dust deposition on the transformer surface is shown on Figure 5. The deposition had been downgrading the transformer HDE by about 3%. Furthermore, low to medium wind speed had been reducing the HDE by another 4-29% range. Only high wind speed could increase heat dissipation from the transformer by about 9-23%. Overall site environment increased thermal stress on the unit.

Site condition #2

Transformer is located at the bottom plinth of hydropower station near water (Figure 6a). The transformer bay opening is oriented on west-south. There are three environmental conditions effecting transformer thermal performance:

- solar radiation that has been described in relevant chapter;
- wind;
- mist produced from river surface bottom level of hydro-power station.

The affects of wind and mist cannot be separated because mist is always present when hydropower station is in operation and wind will always drag the particles.

CFD results of the site condition are shown on Figure 7 for two wind directions. As known from solar radiation chapter there is pronounced harmful impact on transformer external surfaces exposed to the solar load and some marginal impact on internal transformer parts. As a counter affect mist from river surface with a combination of wind has a positive impact on transformer thermal performance that can overweight solar radiation effect (Table 5).

Table 5. HDE on site condition #2

Condition	HDE, %		
	Air Natural Flow	**Wind(west-south)**	**Wind(east-south)**
Solar radiation affect on the outer surface	**-92.5**	**-92.5**	**-92.5**
Mist affect on the outer surface	**1.7**	**73.8**	**114.2**
Solar radiation affect on the internal parts	**-1.51**	**-1.51**	**-1.51**
Mist affect on internal parts	**0.14**	**6.4**	**9.9**

Conclusion

In the article it is identified that CFD modeling can be used to assess affects of mentioned environmental conditions on transformer thermal performance. There is a potential to use the information in minimizing harmful impact and maximizing positive influence of environment on transformer thermal performance. Potentially the information can be used to improve other aspects of the equipment conditions.

It was confirmed by the simulations that certain level of the surrounding factors can significantly impact on transformer thermal performance. Some affects have a positive influence, some – negative and some can have positive or negative depending on their level and combination with other factors.

The topic is at early stage of research and it does not have established data. At present the environmental conditions impacts on thermal performance have to be assessed in case by case basis.

The author wishes to thank Deepak Maini for his kind support and valuable suggestions for the paper.

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Dr Yuriy Odarenko graduated with the M.Eng. degree in Power Engineering at Zaporizhzhya State Engineering Academy, Ukraine in 2002. This study included participating in a research project at the Institute of Polymer Technology of the University of Erlangen-Nuremberg, Erlangen, Germany. Between 2002 and 2008 he was a research fellow at the Thermal Laboratory of the Ukrainian Transformer Institute (VIT), Zaporizhzhya. At VIT he participated in design, technology and R&D of wide range of voltage and power classes of transformers and shunt reactors. He investigated fluid dynamics and heat and mass transfer phenomena in dielectric liquid immersed, SF6 gas insulated and dry types of transformers. In parallel he pursued his Ph.D. in Zaporizhzhya State Engineering Academy (ZGIA), modelling the thermal performance of transformer windings, which he completed in 2007. In 2008 he moved to Melbourne working with the Centre for Power Transformer Monitoring, Diagnostics and Life Management within Monash University. Currently he is working in R&D at the Wilson Transformer Company. He participates in the working groups of CIGRE A2-24 “Thermal Performances of Power Transformers” and IEC TC-14 MT-06 “Thermal Performance of Transformers”.

THE TRANSFORMER PEOPLE

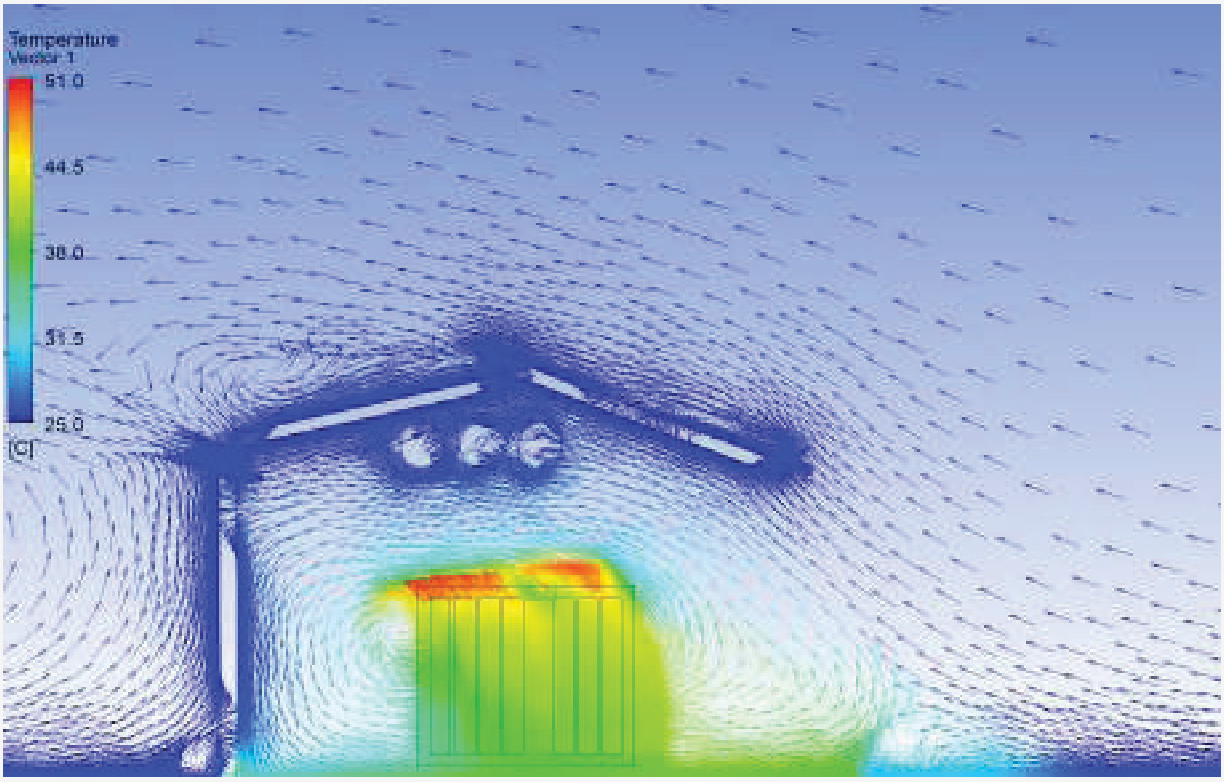


Figure 1
Air flow recirculation zone created by westerly wind

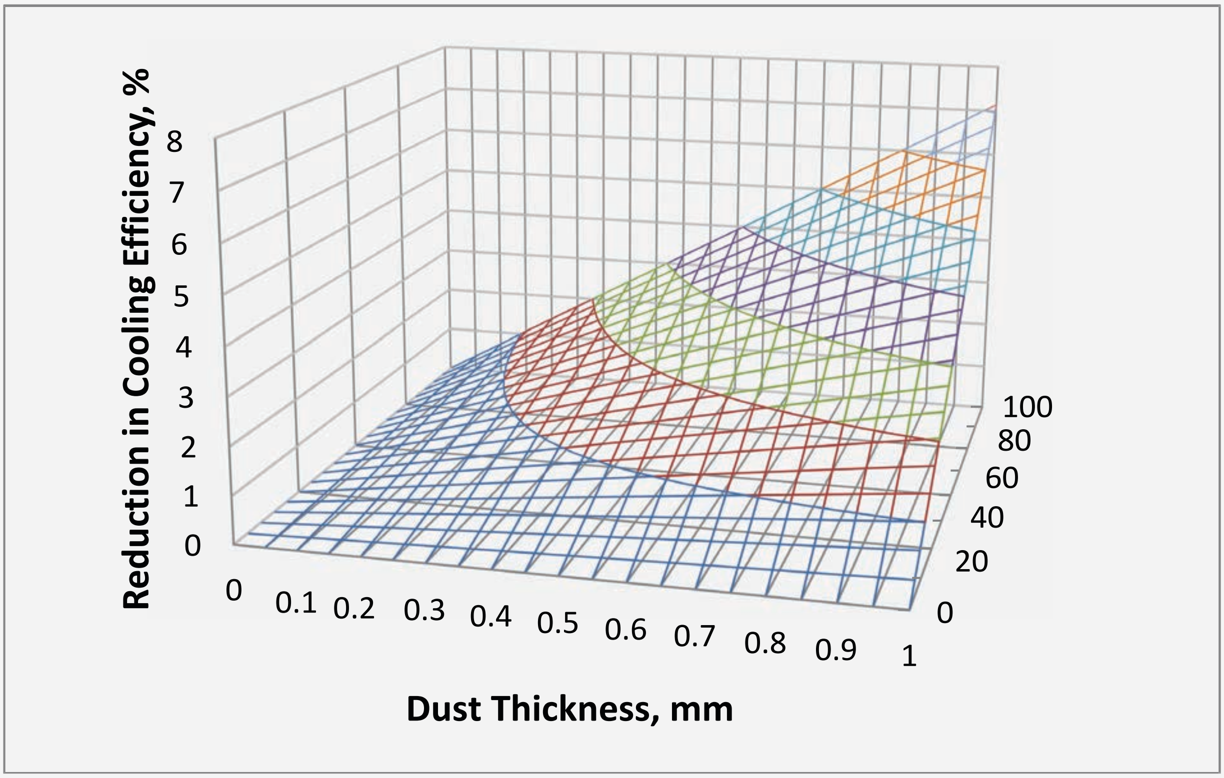


Figure 2
Reduction of transformer cooling efficiency due to its surface contamination with a dust

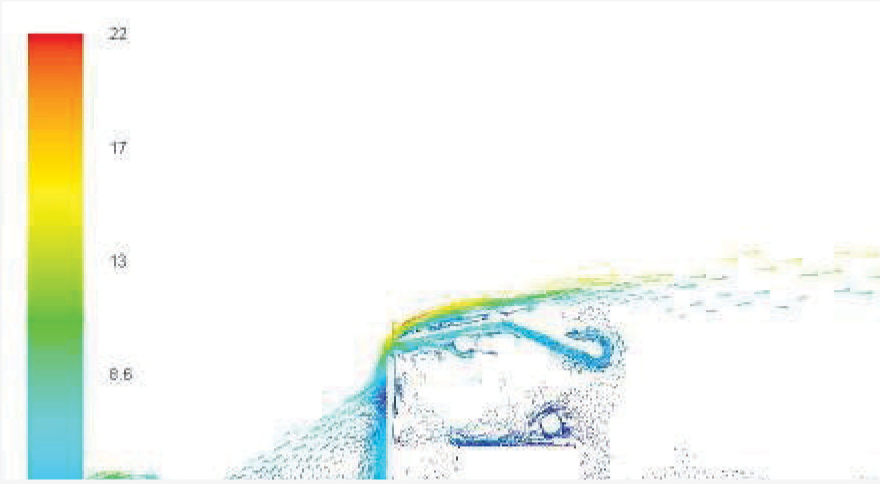


Figure 3
Dust particles velocity in m/s

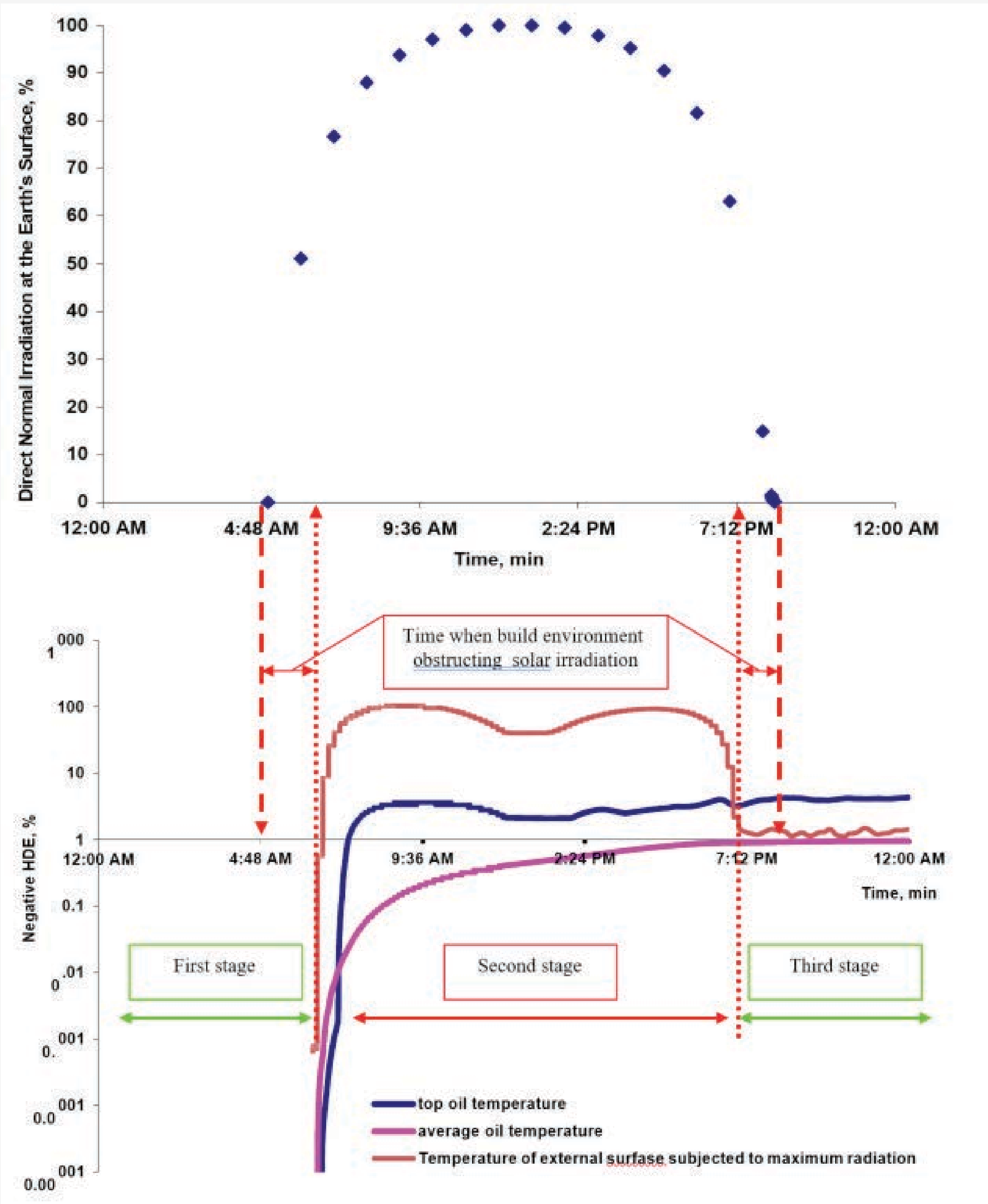
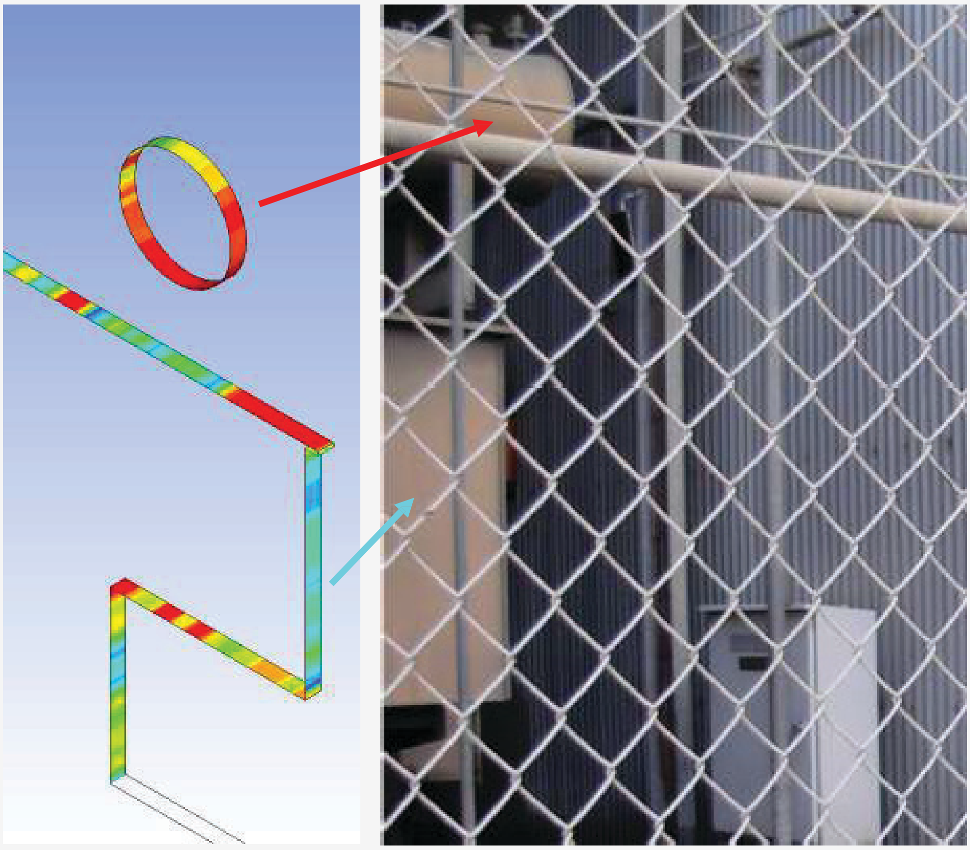


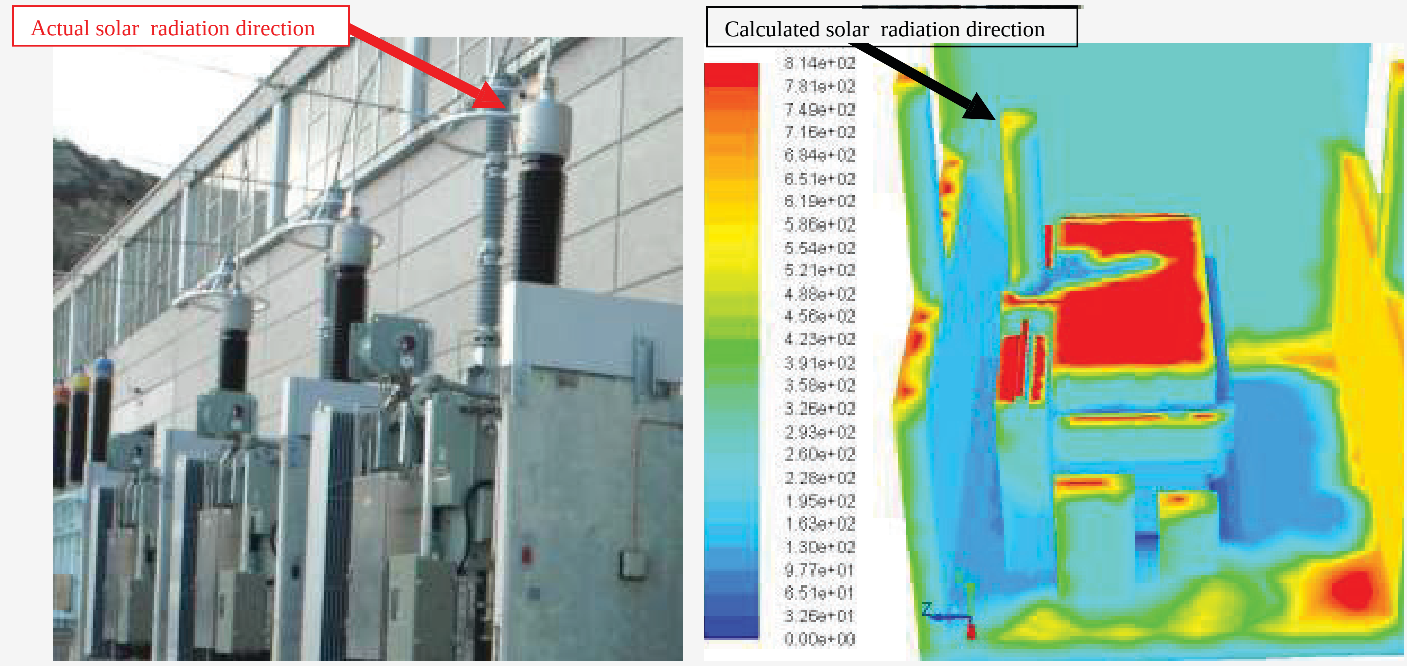
Figure 4
Results of Solar Radiation Loading



a) b)

Figure 5

Comparison of the simulation vs. actual site condition of the localized particle deposition



a) b)

Figure 6

Contours of Solar Heat Flux, W/m^2

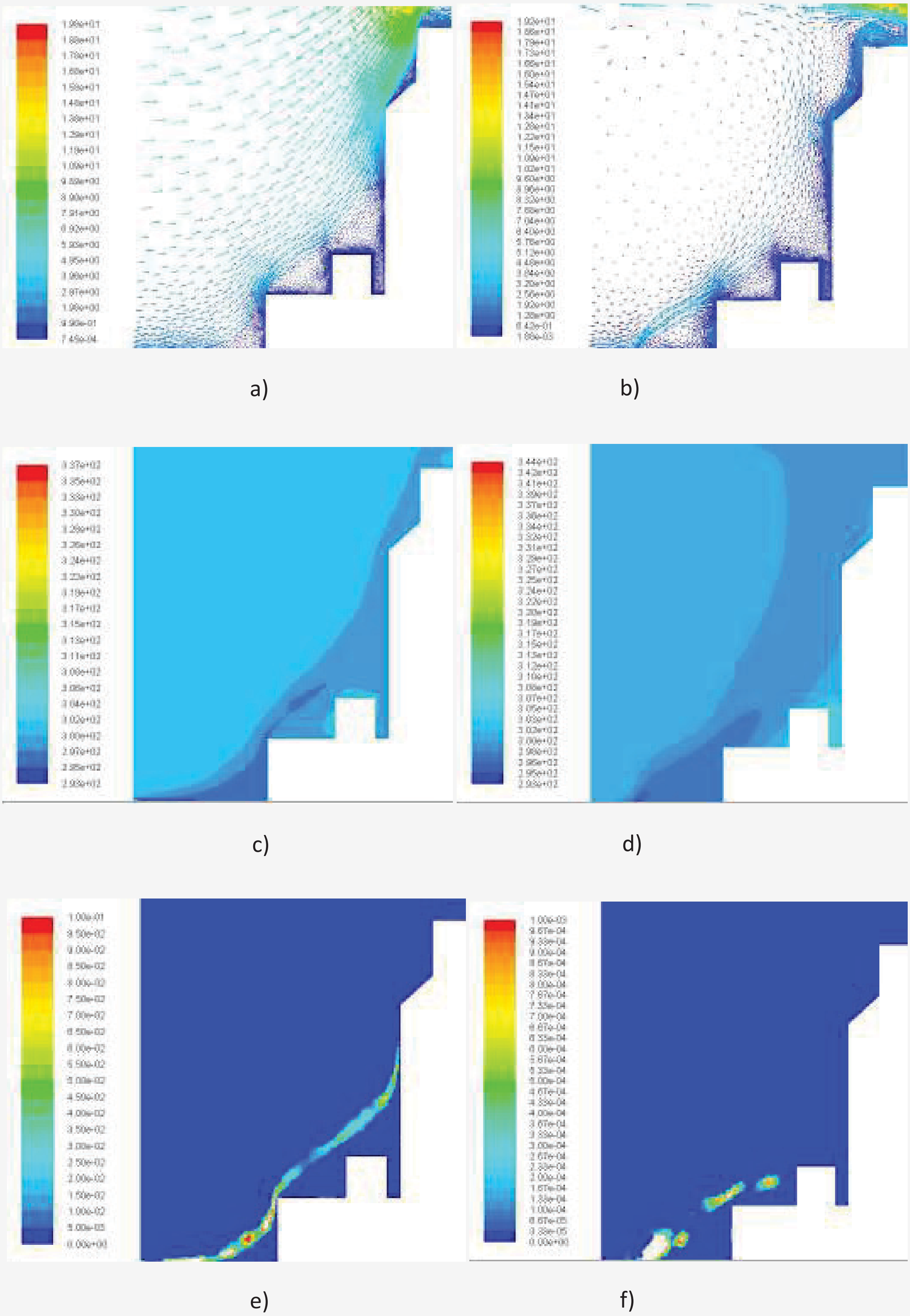


Figure 7

Air velocity in m/s (a, b), temperature in degrees of Kelvin (c, d), water droplets concentration in kg/m3 (e, f) for west-southern (a, c, e) and east-northern (b, d, f) wind direction