VARIATION OF STEADY-STATE THERMAL CHARACTERISTICS OF TRANSFORMERS WITH OFWF COOLING IN SERVICE

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ABSTRACT

The paper presents the thermal model for top oil temperature calculation in transformers with forced oil and water circulation. The model is completely based on the heat-transfer theory. The thermal parameters change in time, due to the sedimentation of substance from the water and the oil to the heat-exchanger surfaces. Fouling factors at water and oil sides can be determined based on measurements. The results of procedure application on the hydro power station block-transformer 2 x 190 MVA / 380 MVA are exposed in the paper. The model is aimed to estimation of transformer loading possibility, but also to maintenance or reconstruction planning purposes.

Key words: Power transformers, Thermal modelling, OFWF cooling

1. INTRODUCTION

In a power transformer operation a part of the electrical energy is converted into the heat. Although this part is quite small comparing to total electric power transferred through a transformer, it causes significant temperature rise of transformer constructive parts, which represents the limiting criteria for possible power transfer through a transformer. That is why the precise calculation of temperatures in critical points (top oil and the hottest solid insulation spot) is of practical interest. The determination of these temperatures represents a complex task.

In a transformer tank, oil streams in a closed space having relatively complex geometry, which results in tedious application of the convection heat transfer theory [1]. Some attempts of heat transfer theory results application to the heat transfer from winding to oil are exposed in [2] and [3]. Vagueness of such approaches is the consequence of conditions divergence in real transformers and in models from which the expressions are established [4, 5]. A common approach to a calculation of heat transfer from oil to external cooling medium (air or water) is not direct application of heat transfer theory, than the use of simplified functional dependencies of oil temperature – external cooling medium gradient from transformer load. Such approaches are used in valid international standards [6], in previous authors publications [4, 7], as well as in recently published papers [8, 9]. The usage of average heat transfer coefficient is typical in a transformer designing process to calculate needed number (area) of cooling surfaces.

It is very convenient, but rear possible to apply known expressions from the heat transfer theory to real power transformers. It is possible when the difference of thermal conditions in transformers and of conditions under which expressions were establish is not significant. Typical cases are directed oil streaming (application of expressions to a winding-oil heat transfer [10]) and forced oil and water (air) streaming (application to a oil-water (air) heat exchange). The second case is treated in the paper. This research work is initialised by the practical problem in 380 MVA transformer operation: the top-oil at continuos rated load sporadically had been overcoming the expected value. The solution of the problem was found in the sedimentation of the substance from water to heat exchanger surface. The thermal model based on heat exchanger theory is developed and discussion of parameters in real operating conditions are exposed in the paper.

2. HEAT EXCHENGER THEORY

2.1. Heat transfer in the exchanger

Heat exchanger used on considered transformer is shown in Fig. 1. The calculation method of heat transfer power from the hot to the cold fluid is well-known in heat transfer theory [11]. First, the equations corresponding to the elementary heat exchanger configuration are solved in a closed analytical form and then the correction coefficients are applied to complete the calculation procedure for a real complex heat exchanger. The elementary heat exchanger configuration, with an opposite fluid streaming directions, is shown in Fig. 2.

Fig. 1 – Real heat exchanger configuration

Fig. 2 – Elementary heat exchanger configuration

Differential power of heat transfer from the hot (oil) to the cold (water) fluid through an elementary surface of heat-exchanger with circular inner tube of diameter *d* is equal

$$dP = p\, d\, U (J_o(x) – J_w(x)) dx. \tag{1}$$

Symbol	Meaning
U	Overall heat transfer coefficient (W / (m^2 K))
$J_o\,(x)$	Oil temperature at position x (^{0}C)
$J_w\,(x)$	Water temperature at position (^{0}C)

Differential power of heat transfer, assuming there exists only the heat exchange between the fluids, can be also expressed as:

$$dP = -m_o c_{po} dJ_o(x) \tag{2}$$

$$dP = -m_w c_{pw} dJ_w(x) \tag{3}$$

Symbol	Meaning
m_o	mass flow rate of the oil (kg / s)
m_w	mass flow rate of the water (kg / s)
c_{po}	specific heat at constant pressure of the oil (J / (kg K))
c_{pw}	specific heat at constant pressure of the water (J / (kg K))

Integrating equations (2) and (3), the following expressions for the cooling power of hot, i. e. for the heating power of cold fluid are obtained:

$$P = m_o c_{po} (J_{oi} - J_{oo}) \tag{4}$$

$$P = m_w c_{pw} (J_{wo} - J_{wi}) \tag{5}$$

Symbol	Meaning
J_{oi}	Temperature of the oil at the input (^{0}C)
J_{oo}	Temperature of the oil at the output (^{0}C)
J_{wi}	Temperature of the water at the input (^{0}C)
J_{wo}	Temperature of the water at the output (^{0}C)

As shown in [11], from expressions (1)–(5) the following formula can be derived:

$$P = \frac{U\,S\left((J_{oi} - J_{wo}) - (J_{oo} - J_{wi})\right)}{\ln\left(\frac{J_{oi} - J_{wo}}{J_{oo} - J_{wi}}\right)}, \tag{6}$$

where S is the total heat exchanger surface.

For complex heat exchangers the equation form

$$P = \frac{U F S\left((J_{oi} - J_{wo}) - (J_{oo} - J_{wi})\right)}{\ln\left(\frac{J_{oi} - J_{wo}}{J_{oo} - J_{wi}}\right)} \tag{7}$$

is used, where F is the correction coefficient; for typical exchangers the values of this coefficient can be found in literature. For the heat exchanger shown in Fig. 1, the value of F can be determined using graphics given in [12], where the next parameters are used:

$$A = \frac{J_{wo} - J_{wi}}{J_{oi} - J_{wo}} \tag{8}$$

$$B = \frac{J_{oi} - J_{oo}}{J_{wo} - J_{wi}} \tag{9}$$

2.2. Overall heat transfer coefficient

Coefficient U represents the reciprocal value of resistance to heat transfer per unit surface of heat exchanger. There are three basic components of the heat transfer: the convection from oil to tubes, the conduction through tubes and the convection from tubes to water. Convection resistances are equal reciprocal value of convection heat transfer coefficients - a_O for oil and a_w for water. The conduction resistance can be calculated as for the simplest case of a flat wall, since the tube thickness is much smaller than its diameter. The basic expression for coefficient U is then

$$U = \frac{1}{\frac{1}{a_o} + \frac{1}{a_w} + R_{l\ tube}}. \tag{10}$$

2.2.1. Convection heat transfer coefficient for water

The coefficient for convection heat transfer from the inner tube surface to the water (a_w) dominantly depends on the water velocity (V_w). The velocity is equal to the ratio of the water flow rate and the total cross-section surface of Nc tubes, each with inner diameter D = 15.7 mm. The coefficient a_w can be calculated using following equations [13], valid for turbulent streaming of a fluid in tubes of circular cross-section:

$$\mathrm{Re} = \frac{V_w \, D}{n_w} \tag{11}$$

$$Nu = 0.023 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}_w^{\;0.4} \tag{12}$$

$$a_w = \frac{l_w \, Nu}{D} \tag{13}$$

Symbol	Meaning
Re	*Reynolds* number
n_w	water kinematic viscosity at temperature J_w (m^2 / s)
Pr_w	water *Prandtl* number at temperature J_w
Nu	*Nusselt* number
l_w	water thermal conductivity at temperature J_w (W / m · K)
J_w	Characteristic water temperature, equal (J_{wi} + J_{wo}) / 2 (^{0}C)

2.2.2. Convection heat transfer coefficient for oil

The coefficient for convection heat transfer from the oil to the outer tube surface (a_o) dominantly depends on the oil velocity (V_o). The velocity is equal to the ratio of the oil flow rate and the cross-section of surface perpendicular to oil streaming, defined by heat exchanger geometry. Coefficient a_o can be calculated using following equations [13], valid for oil streaming over the tube bank:

$$\mathrm{Re} = \frac{V_{o\,\max} \, D}{n_o} \tag{14}$$

$$Nu = C \, \mathrm{Re}^{m} \, \mathrm{Pr}_o (J_o)^{0.36} \left(\frac{\mathrm{Pr}_o (J_o)}{\mathrm{Pr}_o (J_s)} \right)^{0.25} \tag{15}$$

$$a_o = \frac{l_o \, Nu_o}{D} \tag{16}$$

Symbol	Meaning
V_{omax}	Maximum oil streaming velocity occurring within the tube bank (m/ s)
D	Outer tube diameter, approximately equal to the inner diameter (m)
n_o	Oil kinematic viscosity at temperature J_o (m^2 / s)
Pr_o (ϑ_o)	Oil *Prandtl* number at temperature J_o
Pr_o (ϑ_s)	Oil *Prandtl* number at temperature J_s
C, m	Constants
l_o	Oil thermal conductivity at temperature J_o (W / m · K)
J_o	Characteristic oil temperature, equal (J_{oi} + J_{oi}) / 2 (^{0}C)
J_s	The tube bank surface temperature, equal $J_o - (J_o - J_w)\,(1/a_0) / (1/a_0 + R_{l\,tube} + 1/a_w)$ (^{0}C)

Since the tube bank has the staggered configuration, the maximum velocity can occur at either the transverse plane (perpendicular to the main oil streaming direction) or the diagonal plane; analyses of concrete heat exchanger has showed the maximum velocity occurs in the transverse plane. Constants C and m are given in [13] as function of *Reynolds* number value and the ratio of tube centres distance in transverse plane (S_T) and in diagonal plane (S_D); from the value of *Reynolds* number in the range 10^3 – $2 \cdot 10^5$ and ratio (S_T / S_L) < 2, coefficient C is equal $0.35\,(S_T / S_L)^{0.2}$ and coefficient $m = 0.6$.

2.3. Fouling factor

An important phenomena existing in real heat exchangers is reduction of the overall heat transfer coefficient in time, due to the sedimentation of substance from both fluids. The influence of such formed layers can be treated by introducing additional thermal resistances, termed the fouling factors (fD). Their values depend mainly on the service of heat exchanger. Taking into account this thermal resistances, formula (10) becomes the form

$$U = \frac{1}{\frac{1}{a_o} + \frac{1}{a_w} + R_{l\,tube} + fD_o + fD_w}, \quad (17)$$

where fD_o and fD_w are fouling factors for oil and water side, respectively. In [13] the following rough recommendation can be found: for oil fD_o = 0.0009, and for river water fD_w = 0.0001–0.0002.

Using the temperature and load measurements, the overall heat transfer coefficient can be calculated from equation (7); the transferred power is equal the power losses in a transformer and can be calculated from the known transformer load. From the values of U before and after the cleaning of surface from one of the fluids side (for example from the water side), the value of fD_w can be determined, using equation (17) – after the cleaning, fD_w is equal zero.

3. POWER OF THE HEAT TRANSFER THROUGH THE HEAT EXCHANGER

The power transferred through each of two heat exchangers (P) from the oil to the water in thermal steady-states is somewhat lower than the half of the power losses in the transformer (P_g). The difference is caused by the heat transfer from the tank surface by the natural ambient air free convection (P_a):

$$P = \frac{1}{2}\left(P_g - P_a\right). \quad (18)$$

The power losses consist of the iron core power losses, which are approximately constant and their value can be taken from the no-load test (P_{Fe}), and of the losses due to the load current. The second component is approximately equal to $P_I = P_{Ir}\,(I / I_r)^2$, where are: P_{Ir} power losses in the short-circuit test at the rated current (I_r) and the rated temperature, and I is the transformer load. The precision of P_I estimation is higher as the current is closer to the rated value [14].

The power of heat transfer P_a can be approximately calculated in the following manner. Let us denote the total area of the tank as S_t and the tank high as L. The value of heat transfer coefficient from the tank surface to the surrounding air (a_a) is calculated as for the vertical surface of area S_t and of high L. It is adopted that the surface has the constant temperature, equal to the value calculated from the measured ones on the tank at the top (J_{tt}), at the middle high (J_{tm}) and at the bottom (J_{tb}):

$J_t = ((J_{tt} + J_{tb}) / 2 + J_{tm}) / 2$. Coefficient a_a can be calculated using the following equations [13]:

$$Gr = \frac{b\, g\, L^3 \left(J_t - J_a\right)}{n_f^2} \tag{19}$$

$$Ra = Gr\, \mathrm{Pr}_f \tag{20}$$

$$Nu = 0.1\, Ra^{1/3} \tag{21}$$

$$a_a = \frac{l_f\, Nu}{L} \tag{22}$$

Symbol	Meaning
Gr	*Grashof* number
b	Volumetric thermal expansion coefficient, equal $1 / (273 + J_f)$ (K^{-1})
g	Gravitational acceleration ($9.81\ m / s^2$)
L	High of the tank (4 m)
n_f	Air kinematic viscosity at temperature J_f (m^2 / s)
Ra	*Rayleigh* number
Pr_f	Air *Prandtl* number at temperature J_f
l_f	Air thermal conductivity at temperature J_f ($W / m \cdot K$)
J_f	Characteristic air temperature, equal $(J_t + J_a) / 2$ (^0C)
J_a	Ambient air temperature (^0C)

The expression (21) is valid if $Ra > 10^9$.

The power of heat transfer due to the natural air free convection is equal to

$$P_a = a_a\, S_t \left(J_t - J_a\right). \tag{23}$$

4. STEADY-STATE THERMAL MODEL

The model is intended to a steady-state top-oil temperature calculation, at different transformer current loads (I) and different inlet water temperatures (J_{wi}). The flow rates of the oil and the water, the fouling factors from the water and the oil sides, as well as the oil parameters are considered as known. It is shown in Section 6. how the flow rates and the fouling factors can be determined experimentally.

First, the power losses P_g should be calculated. Then, the power transferred from the tank surface to the ambient air (P_a) can be approximately calculated from ambient air temperature and roughly esteemed tank temperature, using Eqs. (19) – (23). Since this power is about 2 % of power losses its simplified calculation satisfies. Anyway, the power P_a could be calculated more precisely through uncomplicated iterative procedure. Using Eq. (18), the power of heat transfer in each of the heat exchangers can now be calculated.

The water temperature at the outlet from the heat exchanger is equal

$$J_{wo} = J_{wi} + \frac{P}{m_w\, c_{pw}}. \tag{24}$$

The oil temperatures at the inlet and the outlet can be calculated starting from following two equations:

$$P = \frac{U((J_{oi} + J_{oo})/2)\, F\, S\, \left((J_{oi} - J_{wo}) - (J_{oo} - J_{wi})\right)}{\ln\left(\dfrac{J_{oi} - J_{wo}}{J_{oo} - J_{wi}}\right)} \tag{25}$$

$$J_{oo} = J_{oi} - \frac{P}{m_o\, c_{po}} \tag{26}$$

Coefficient U in Eq. (25) is temperature dependent, since its component a_o depends on oil temperatures J_{oi} and J_{oo}. The analytical expressions for temperature dependence of oil parameters are used. In such a way, unique system of non-linear equations, including Eqs. (11) – (17), is established; solving the system, oil temperatures J_{oi} and J_{oo} can be determined. Note that the temperature J_{oi} is approximately equal to the top-oil temperature.

5. DESCRIPTION OF THE TRANSFORMER AND THE MEASUREMENTS

Measurements were done on the hydro power station block-transformer of rated power 2 x 190 MVA / 380 MV, with rated voltage at lower (generator) side U_{rl} = 15.75 kV and at higher (network) side U_{rh} = 420 kV. The rated power losses, determined from factory tests, amount to P_{Fe} = 318 kW (no-load losses) and P_{Ir} = 780 kW (losses due to the rated current at the rated average winding temperature of 75 ^{0}C).

The heat transfer from the oil to the water runs through two heat-exchangers oil-water, each of the outer diameter 300 mm and length 2.5 m, of the construction shown in Fig. 1. The water flows througt 105 tubes of U profile, of diameter D = 15.7 mm. The tank surface area amounts to S_t = 160 m^2 and the high L = 4 m. Since the water flow measurement was not reliable and the oil flow measurement did not exist, the oil and the water flows were estimated from the oil and water temperatures measured at the inlets and the outlets of the heat-exchanger.

The following temperature values were measured: of the oil and of the water at the inlet and at the outlet of both heat exchangers (8 measuring positions), the tank temperatures at the bottom, middle and top (3 measuring positions), the top oil temperature and the ambient air temperature. The period of measurements was 1 min; thermocouples of type T were used for temperature measurements.

In order to calculate the transformer power losses, depending on the transformer load, the voltages, currents, active powers and reactive powers in all three phases were measured and recorded. The measurements were done in high voltage substation.

As an example, on Figs. 3 to 5 some measuring results are shown. They relate to the situation when the heat-exchanger surface adjoining the water was cleaned before two months. Commonly, cleaning period is 4 to 5 months. The heat-exchanger surface adjoining the oil was not cleaned for a many years of transformer operation, although it is possible to clean it.

Fig. 3 – Transformer loading diagram

Fig. 4 – Change of characteristic temperatures

Fig. 5 – Oil to water temperature gradients

6. CALCULATION RESULTS

6.1. Fouling of the heat-exchanger

Table 1 contains measured temperatures of the oil and the water at the inlet and at the outlet of the heat exchanger, as well as of the top oil (J_{to}), the tank (J_t) and the ambient air (J_a), all for the steady state reached with transformer load of 362 MVA, resulting the power losses of 1026 kW. Two measurements were done: the first one before the cleaning of heat-exchanger surface adjoining water and the second one after the cleaning.

Table 1

Based on the measuring results, the following is calculated: the power of cooling by natural ambient air free convection (P_a) from Eqs. (19)–(23); the power of cooling through each of heat exchangers oil/water (P) using Eq. (18); the oil and water mass flow rates from Eqs. (4) and (5), respectively – by simple dividing of the mass flow rate with the density flow rates (q) are calculated; overall heat transfer coefficient using Eq. (7). The calculation results are shown in Table 2.

Table 2

The overall heat transfer coefficient at dirty conditions is 15 % lower than the value for the clean heat exchanger. From these two overall heat transfer coefficient values, the fouling factor for the water side can be calculated using Eq. (17); so obtained value fD_w = 0.0002781 is about 40 % higher than the one recommended in [13].

Applying Eqs. (11) – (13) for the convection surface-water heat transfer coefficient and Eqs. (14) – (17) for the convection oil-surface heat transfer coefficient, we obtain a_w = 2510 W/(m^2 K) and a_o = 3196 W/(m^2 K). The value of heat resistance (per surface unit) to the conduction through the tube amounts to $R_{I\,tube}$ = 2.653 · 10^{-6} (K/W) m^2. From Eq. (10), the overall heat transfer coefficient in the case of ideally clean surfaces adjoining the water and the oil is equal 1401 W/(m^2 K). From this and the value of overall heat transfer coefficient at clean water side (608 W/m^2 K), the fouling factor for oil side can be calculated using Eq. (17), where fD_w = 0; so obtained value fD_o = 0.000931 is approximatelly equal (only 3.4 % higher) the value reccomended in [13] (0.0009). Note that the sedimentation of the materies from oil reduces the overall heat transfer coefficient to 43 % of the value by ideally clean heat-exchanger.

6.2. Influence of the oil flow rate

A practical background for this group of calculation is possible decrease of the oil flow during a transformer long-time operation, caused by an attenuation of oil pumps. The oil flow was varied in the range 80 %-120 % of the value in the moment of done measurements. The calculations were made for the inlet water temperature J_{wi} = 6.7 ^{0}C, transformer load 362 MVA and adopted approximate value of cooling by the ambient air P_a = 20 kW and dirty heat exchanger (fD_o = 0.000931 and fD_w = 0.0002781).

From Eq. (24), where P is equal 503 kW, the outlet water temperature amounts to J_{wo} = 17.4 ^{0}C. Solving the system of Eqs. (25), (26) and those covering the overall heat transfer coefficient U the following results were attained. Coefficient U varies from 496.4 W / (m^2 K), valid for the minimal oil flow, to 518.5 W / (m^2 K), valid for the maximal oil flow. The temperature ranges are: J_{oi} – from 57.8 ^{0}C (max. oil flow) to 63.9 ^{0}C (min. oil flow), J_{oo} – from 39.2 ^{0}C (min. oil flow) to 41.3 ^{0}C (max. oil flow), $J_{oi} - J_{oo}$ from 16.4 K (max. oil flow) to 24.6 K (min. oil flow).

6.3. Comparison with the algorithm from IEC standards

The aim of this group of calculations was to check the accuracy of the simplified procedure from valid international standards [6]. In this analysis the problem of thermal parameters change during the long-term service is left out, i. e. the temperature values for fixed cleanness and oil flow rate are compared for different loads. Characteristic temperature values, used in the algorithm from [6] are adopted to be equal to the ones from the measurements at dirty conditions. The differences of temperatures calculated using the model from [6] and the ones calculated by the exposed model are in the range: [-0.092, 0.312] K for the bottom oil and [-2.853, 0.996] K for the top oil; the differences increase with the increase of load, varied in the range [200, 500] MVA.

7. PROSPECT FOR FUTURE WORK

The proposed steady-state model can be extended for the calculation of the top oil temperature during transient thermal processes. The power of heat accumulation in oil (of the thermal capacity C_o) is equal the instantaneous power losses minus cooling power. This power is equal the product of C_o and oil temperature derivation; as the representative oil temperature can be adopted the temperature of top-oil. When this differential equation is transformed in difference equation, the top oil temperature in the next discrete time instant can be easily calculated. Procedure requires the top oil temperature in the initial moment (t = 0) to be known. It means that for the cooling power calculation the value J_{oi} is known (of course, the value of J_{wi} is also known). The value of J_{oo} can be from Eq. (26) expressed as function of J_{oi} and P, while J_{wo} can be from Eq. (24) expressed as function of J_{wi} and P. Inserting this into Eq. (25), the equation with one unknown – the cooling power in heat exchanger – is reached. Cooling power from the tank surface can be calculated using Eqs. (26) and (19) – (23), assuming that the tank temperature is equal the mean value of J_{oi} and J_{oo}.

Thermal steady-states and transient heat processes in copper can be treated by one of known methods. Introducing this, the power of winding to oil heat transfer should be used instead of winding power losses for the top-oil calculation.

8. CONCLUSIONS

The steady-state thermal model for top-oil temperature calculation in transformers with OFWF or ODWF cooling is exposed in the paper. The exposed procedure is completely based on the heat exchanger theory.

From the measurements realised on 380 MVA transformer the factors characterising deterioration of cooling system performances during the operation are defined. The important conclusion is that transformer loading capability changes in time – it decreases from the moment when the surfaces of oil-water heat exchangers are clean till the moment of a new cleaning. The worsening of transformer thermal parameters have to be accounted in the calculation of the insulation ageing. The valid international standards for transformer loading does not treat this phenomena.

An influence of other cooling system parameters change can be also esteemed on the developed model. The example of the oil flow reduction (due to the oil pump weakening) influence is exposed in the paper. In that sense, the model can be useful in the planing of: operational maintenance, partial or complete reconstruction of pumps, change of heat-exchangers (everything to keep the current transformer loading capability or to increase it).

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Table 1 – Measured temperature values

	Clean	Dirty
J_{to} (^{0}C)	53.8	61.5
J_{oi} (^{0}C)	54.5	60.1
J_{oo} (^{0}C)	34.5	40.5
J_{wi} (^{0}C)	6.5	6.7
J_{wo} (^{0}C)	17.1	17.4
J_t (^{0}C)	36.1	44.7
J_a (^{0}C)	0.3	10.5

Table 2 – Calculated relevant thermal characteristics

	Clean	Dirty
P_a (kW)	22.82	20.45
P (kW)	501.5	503
q_o (lit/s)	14.354	14.564
q_w (lit/s)	11.391	11.268
U (W/m^2 K)	608	520

List of figures:

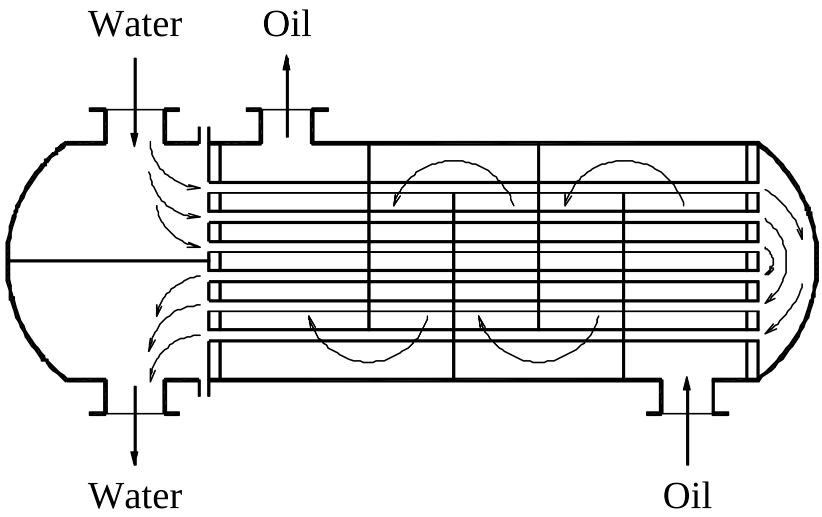

Fig. 1

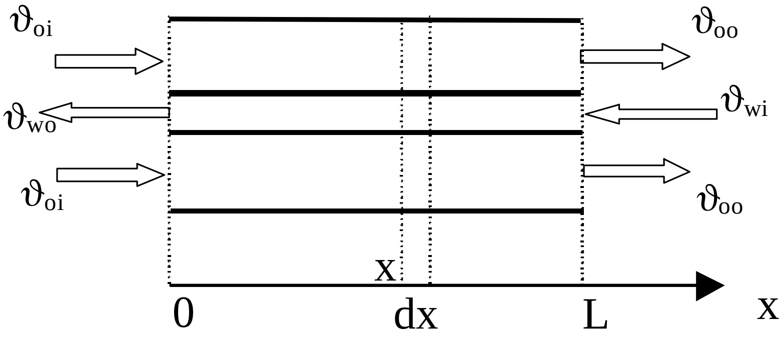

Fig. 2

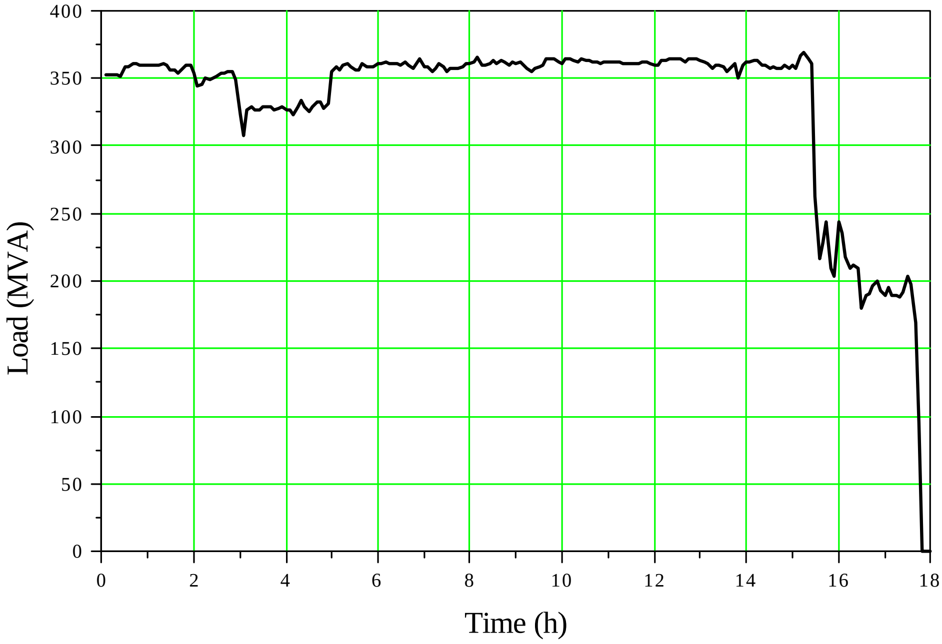
400
350
300
250
200
150
100
50
0
Load (MVA)
0
2
4
6
8
10
12
14
16
18
Time (h)

Fig. 3

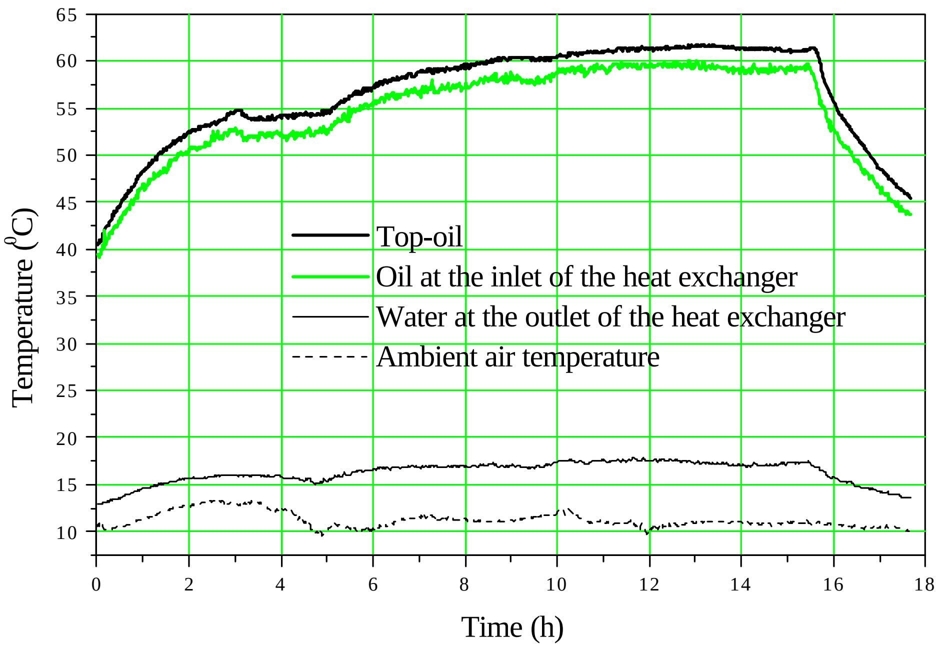
Temperature (^{0}C)
65
60
55
50
45
40
35
30
25
20
15
10
0
2
4
6
8
10
12
14
16
18
Time (h)
Top-oil
Oil at the inlet of the heat exchanger
Water at the outlet of the heat exchanger
Ambient air temperature

Fig. 4

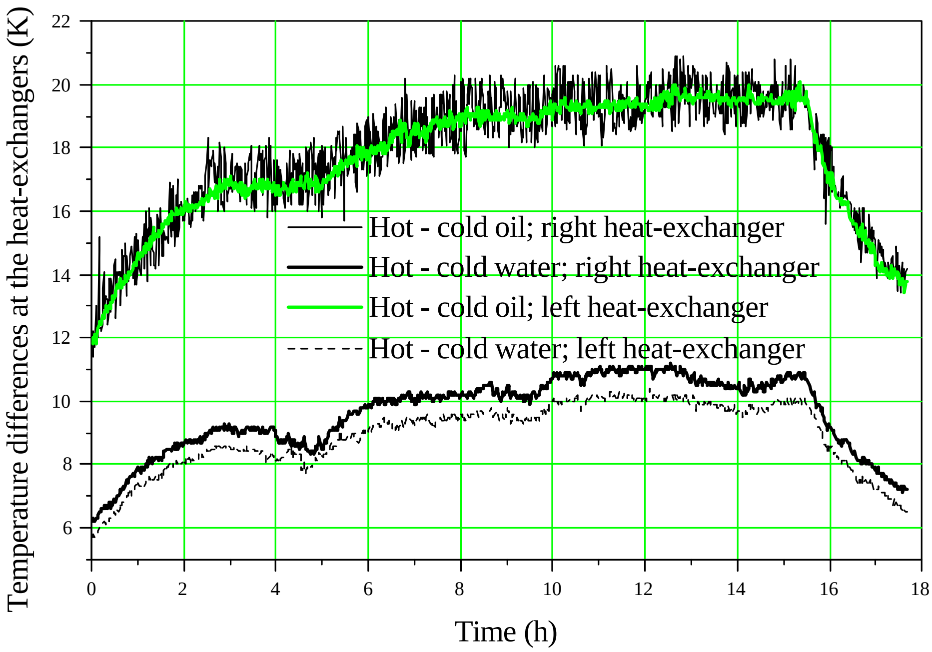
Temperature differences at the heat-exchangers (K)
22
20
18
16
14
12
10
8
6
0
2
4
6
8
10
12
14
16
18
Time (h)
Hot - cold oil; right heat-exchanger
Hot - cold water; right heat-exchanger
Hot - cold oil; left heat-exchanger
Hot - cold water; left heat-exchanger

Fig. 5