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Numerical study of heat transfer and fluid flow in a power transformer ☆

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Abstract

In this paper we study the heat transfer and fluid flow in a step-down 3-phase power transformer. In order to simplify the study we choose an element composed of two windings wound around a core. The Joule effect and the Foucault currents produce an undesirable heat in the different components of the transformer. From an economical and security point of view, there is a need to cool the transformer to preserve it from destruction. Our main objective is the cooling optimization of the power transformer. In order to attain this goal, a numerical study has been conducted for six different geometric configurations with six different flow rates of the cooling oil at the entrance. The physical properties of the fluid are supposed to be function of the temperature. The control volume method has been used to resolve the continuity, the momentum and the energy equations in the steady state. The obtained results show that the structure of the flow is somehow complex and according to the case some rolls appear at the top and the bottom of the windings, these rolls contribute to a good mixing of the fluid leading to a nearly homogeneous temperature.

Keywords: Power transformer; Axisymmetric geometry; Mixed convection; Variable physical properties; Control volume method; Cooling; Optimization

1. Introduction

Power transformer is a device employing the principle of mutual induction to convert variations of alternating current in a primary circuit into variations of electrical parameters like voltage and current in a secondary circuit at the same frequency. A typical transformer is composed of two or more coils of insulated conducting wire which are wound around a ring of iron constructed of thin isolated laminations or sheets. The iron ensures that nearly all the lines of force of magnetic field passing through one circuit also pass through the second circuit and that, in fact, essentially all the magnetic flux is confined to the iron. Each turn of the conducting coils has the same magnetic flux; thus, the total flux for each coil is proportional to the number of turns in the coil.

The efficiency of a transformer is less than unity because of losses occurring in the different circuits, due firstly to the variation of the alternate magnetic flux in the iron and secondly to the Joule effect and Foucault currents which produce an undesirable by-product heat. The heating of the transformer must be less than a given value taking into account the type, the power and the components of the transformer. Under this condition, a transformer can work correctly during 20 years, but an increase of 6 °C over the specified limit can reduce this duration by a half [1]. So, from an economical and security point of view, it is necessary to cool the transformer to preserve it. A mineral oil which is a dielectric heat conducting fluid is generally used to achieve this objective.

In the literature, few studies have been made on the heat transfer and the fluid flow inside a power transformer. Recently Mufuta and Van Den Bulck [2,3] studied the case of a winding disc-type transformer and they showed the influence of $Re\,Gr^{-1/2}$ on the flow structure and they give some correlations to calculate the heat transfer inside this kind of transformer. In

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Nomenclature

c_p	specific heat at constant pressure	$J \cdot kg^{-1} \cdot K^{-1}$
h	heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
q	heat rate	W
$\dot{q}$	heat flux	$W \cdot m^{-2}$
$\vec{n}$	normal vector to the surface	
P	pressure	Pa
r	radial coordinate	m
S	surface	m^2
T	temperature	K
u	mean velocity	$m \cdot s^{-1}$
U	axial velocity	$m \cdot s^{-1}$
V	radial velocity	$m \cdot s^{-1}$
$\dot{V}$	volume flow rate	$m^3 \cdot s^{-1}$
x	axial coordinate	m

Greek symbols

μ	dynamic viscosity	$kg \cdot m^{-1} \cdot s^{-1}$
ρ	mass density	$kg \cdot m^{-3}$

Subscripts

a	air
b	bulk
1	horizontal surfaces
2	vertical surfaces

this paper, we present a numerical study of heat transfer and fluid flow inside an element of a 3-phase 40 MVA power transformer composed of two windings wound around a core.

2. Description and modeling

The transformer considered here is a step-down one, the primary and secondary voltages are 110 kV and 20.5 kV respectively. We study the case of steady state. The physical properties of the fluid are supposed to be function of the temperature. Due to the geometrical, mechanical and thermal complexity of the problem, some hypotheses have been made. We suppose that the core and the windings are perfect cylinders crossed by cooling channels. There is one channel inside the core and another one in the secondary windings but two channels in the case of the primary windings. The fluid entrance and exit are located respectively at the bottom and at the top of the core axis, their diameters have the same value 0.06 m. In this manner, the problem becomes an axisymmetric one. The oil absorbs heat from the core and the windings and delivers it to the ambient air across the tank surface and an external heat exchanger. Fig. 1 shows a longitudinal cross section of the transformer.

The cooling channels of the core and the primary windings have a width of 0.005 m but that of the secondary windings is about 0.018 m. The separating core/primary windings channel width and that one separating the two windings are about 0.02 m and 0.038 m respectively.

The convective heat fluxes with the ambient air at the temperature T_a are given by:

$$\dot{q}_1 = h_1(T - T_a) \tag{1}$$

for the horizontal surfaces, and

$$\dot{q}_2 = h_2(T - T_a) \tag{2}$$

for the vertical ones. Different global heat transfer coefficients have been calculated for the bottom, the upper and the lateral faces of the tank. These values are found to be 5.12 $W \cdot m^{-2} \cdot K^{-1}$ and 2.71 $W \cdot m^{-2} \cdot K^{-1}$ for h_1 and h_2 respectively. The inlet velocity of the fluid is supposed to be constant and uniformly distributed at the entrance.

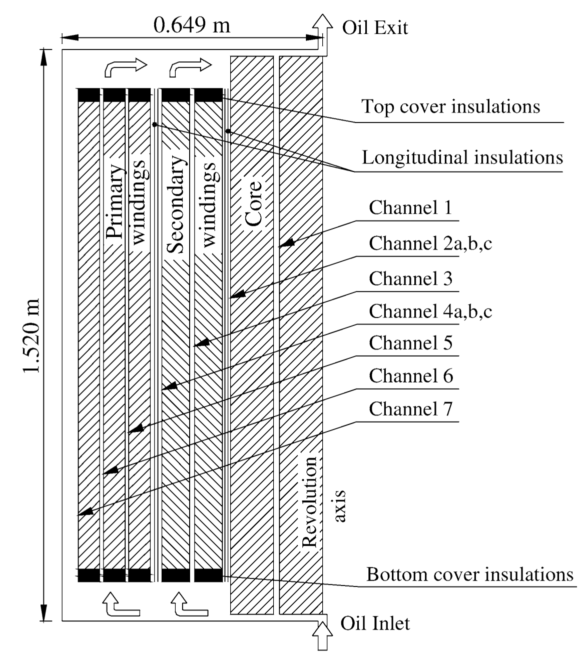

Fig. 1. Description of the transformer.

Moreover, six geometrical configurations have been used. They are obtained by adding to the previously described basic case some insulating materials covering both the top and the bottom of the windings and other longitudinal ones separating the windings from the core and the primary windings from the secondary one as well. These insulations are usually used by the transformer manufactures for electrical reasons but they are not indispensable for its good functioning. The different configurations corresponding to the six cases are as the following:

(1) Basic case, without insulations.
(2) With covering insulations on the top and the bottom of the windings.
(3) With longitudinal insulations only.
(4) With covering insulations on the top and the bottom as well as longitudinal ones.
(5) With double longitudinal insulations only.

Table 1
The heat rate and the heat flux produced by the active parts of the transformer

	Heat rate q [W]	Heat flux $\dot{q}$ [$W \cdot m^{-2}$]	
		Case A	Case B
Core	13515	748	748
Primary windings	84534	1047	1081
Secondary windings	70074	1860	1946

Table 2
The physical properties of the different transformer elements

	Density ρ [$kg \cdot m^{-3}$]	Specific heat c_p [$J \cdot kg^{-1} \cdot K^{-1}$]	Conductivity k [$W \cdot m^{-1} \cdot K^{-1}$]
Core (iron)	7650	478.39	72.39
Windings (copper)	8933	390.84	412.68
Insulations (class A)	7900	504.74	16.14

(6) With covering insulations on the top and the bottom and double longitudinal ones.

The heat produced by every active part of the transformer is supposed to be uniformly distributed on its surface. The numerical values of their heat fluxes for cases without any cover insulations (case A), as well as for the cases with the cover insulations (case B) are given in Table 1. As we can see, due to a higher voltage in the primary windings the heat rate dissipated by this element is greater than that produced by the secondary ones. But the bigger radii of the primary windings with the two cooling channels inside it give these windings a greater contact surface with the oil, which will lead to a smaller dissipated heat flux on its surface, and consequently to higher temperatures on the secondary windings surface. The physical properties of the different elements in the transformer are given in Table 2.

The physical properties of the mineral oil vary with the temperature according to the correlations given by the following equations:

$$\rho(T) = 1098.72 - 0.712T \tag{3}$$

$$k(T) = 0.1509 - 7.101\text{E}{-}05T \tag{4}$$

$$c_p(T) = 807.163 + 3.58T \tag{5}$$

$$\mu(T) = 0.08467 - 0.0004T + 5\text{E}{-}7T^2 \tag{6}$$

From these equations we can see that the density, the thermal conductivity and the dynamic viscosity decrease with increasing temperature, but the specific heat at constant pressure varies in the same way as the temperature.

3. Solution

The problem is described by the continuity, the momentum and the energy equations in the polar coordinates:

$$\frac{\partial(\rho U)}{\partial x} + \frac{1}{r}\frac{\partial(r\rho V)}{\partial r} = 0 \tag{7}$$

$$U\frac{\partial(\rho U)}{\partial x} + V\frac{\partial(\rho U)}{\partial r} = \rho g_x - \frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\mu\frac{\partial U}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial U}{\partial r}\right) \tag{8}$$

$$U\frac{\partial(\rho V)}{\partial x} + V\frac{\partial(\rho V)}{\partial r} = \frac{\partial P}{\partial r} + \frac{\partial}{\partial x}\left(\mu\frac{\partial V}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial V}{\partial r}\right) \tag{9}$$

$$U\frac{\partial(c_p\rho T)}{\partial x} + V\frac{\partial(c_p\rho T)}{\partial r} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) \tag{10}$$

To resolve these equations, a computational program named Fluent based on the control volume method have been used with a PISO (the pressure-implicit with splitting of operators) algorithm, which is part of the SIMPLE family of algorithms, based on the higher degree of the approximate relation between the corrections for pressure and velocity. To improve the efficiency of the calculation, the PISO algorithm performs two additional corrections: neighbour correction and skewness correction. A fully implicit numerical scheme is employed, in which upwind differences are used for the convective terms and central differences for the diffusion terms. Moreover, a structured non uniform mesh of 781×418 cells have been chosen with smaller cells near the walls and larger ones inside the flow to take into account the big difference in the boundary layers near the walls. The calculation is an iterative one, the chosen convergence criteria are 10^{-6} for the temperature and 10^{-4} for both the pressure and the velocities. A parametric investigation concerning the fluid inlet velocity has been conducted to study its influence on both fluid flow and heat transfer.

4. Results

As our main objective is the cooling optimization of the power transformer, we have made use of the different geometric configurations with increasing inlet fluid velocities varying from 0.5 $m \cdot s^{-1}$ to 1.7 $m \cdot s^{-1}$ by taking the intermediate values of 0.85, 1.0, 1.2, 1.5 $m \cdot s^{-1}$. The inlet oil temperature is maintained at 338 K. The ambient air is supposed to be 293 K. In order to study the influence of the different parameters on both the heat transfer and the fluid flow we have made use of the isotherms plots at the top of the transformer, as well as the streamlines plots on both its top and bottom. Moreover, we calculate the highest and the bulk temperature as well as the volume flow rate at every channel, to be able to locate those ones where there is a difficulty to evacuate the heat produced by the different transformer elements.

The volume flow rate and the bulk temperature are given by [4]:

$$\dot{V} = \int_S u \cdot \vec{n} \cdot \mathrm{d}S \tag{11}$$

$$T_b = \frac{\int_S \rho \cdot c_p \cdot T \cdot u \cdot \vec{n} \cdot \mathrm{d}S}{\int_S \rho \cdot c_p \cdot u \cdot \vec{n} \cdot \mathrm{d}S} \tag{12}$$

4.1. Case 1

At the entrance, the fluid flows in a narrow space and continue under the core. After this passage, it will reach a larger

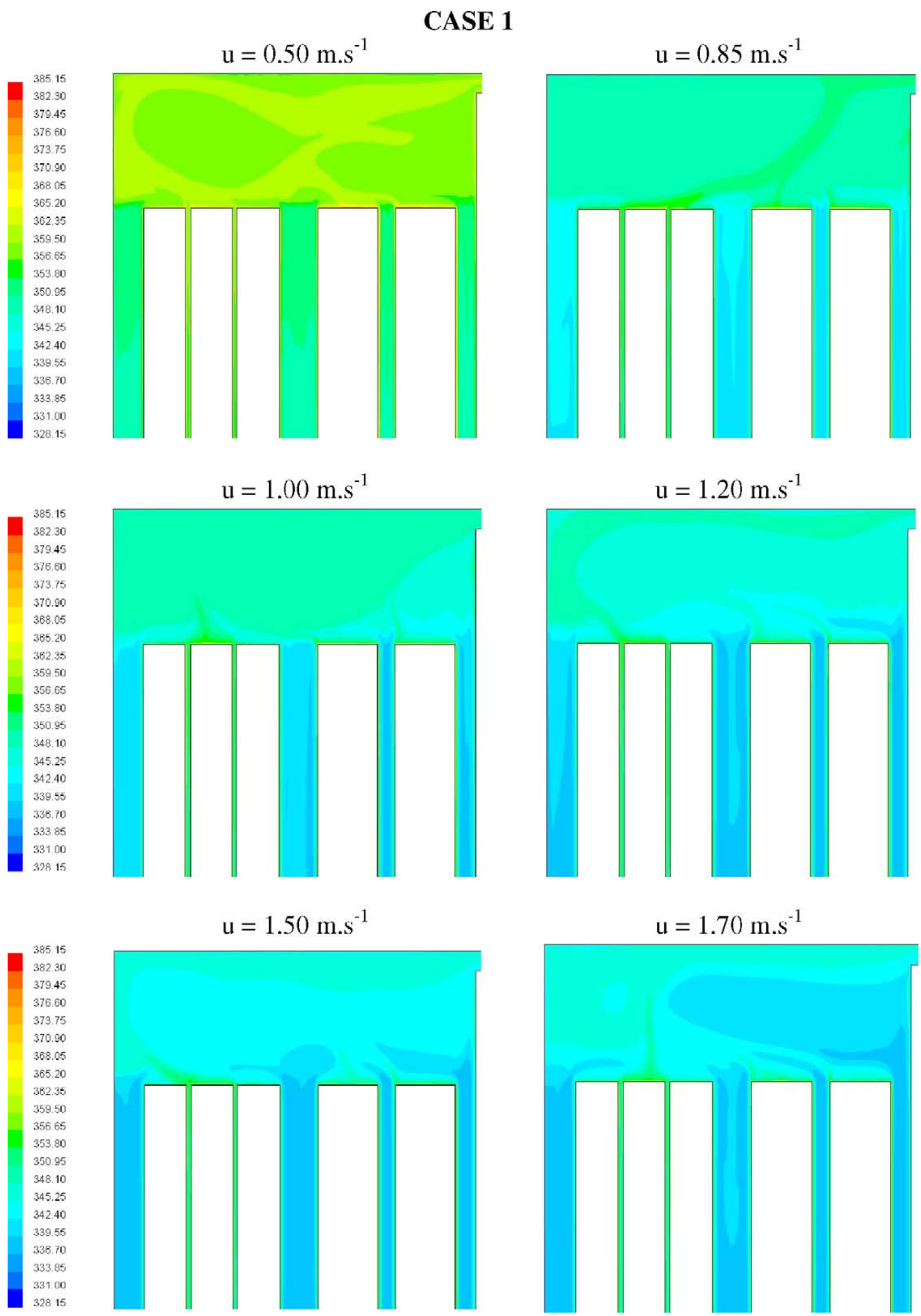

Fig. 2. The isotherms plots at the top of the transformer for different inlet velocities in case 1.

space under the hot windings surfaces. Then, it will absorb heat energy generated by these ones and will go up through the cooling and separating channels aided by the pressure at the entrance and the natural convection produced by the very hot channels walls.

For low inlet velocities, the fluid flow in the different channels is nearly the same (Fig. 4). Moreover, we can observe a big movement of the fluid at the top of the transformer (Fig. 3). This agitation leads to a good mixing of the fluid and consequently to more homogeneous temperature (Fig. 2). The high-

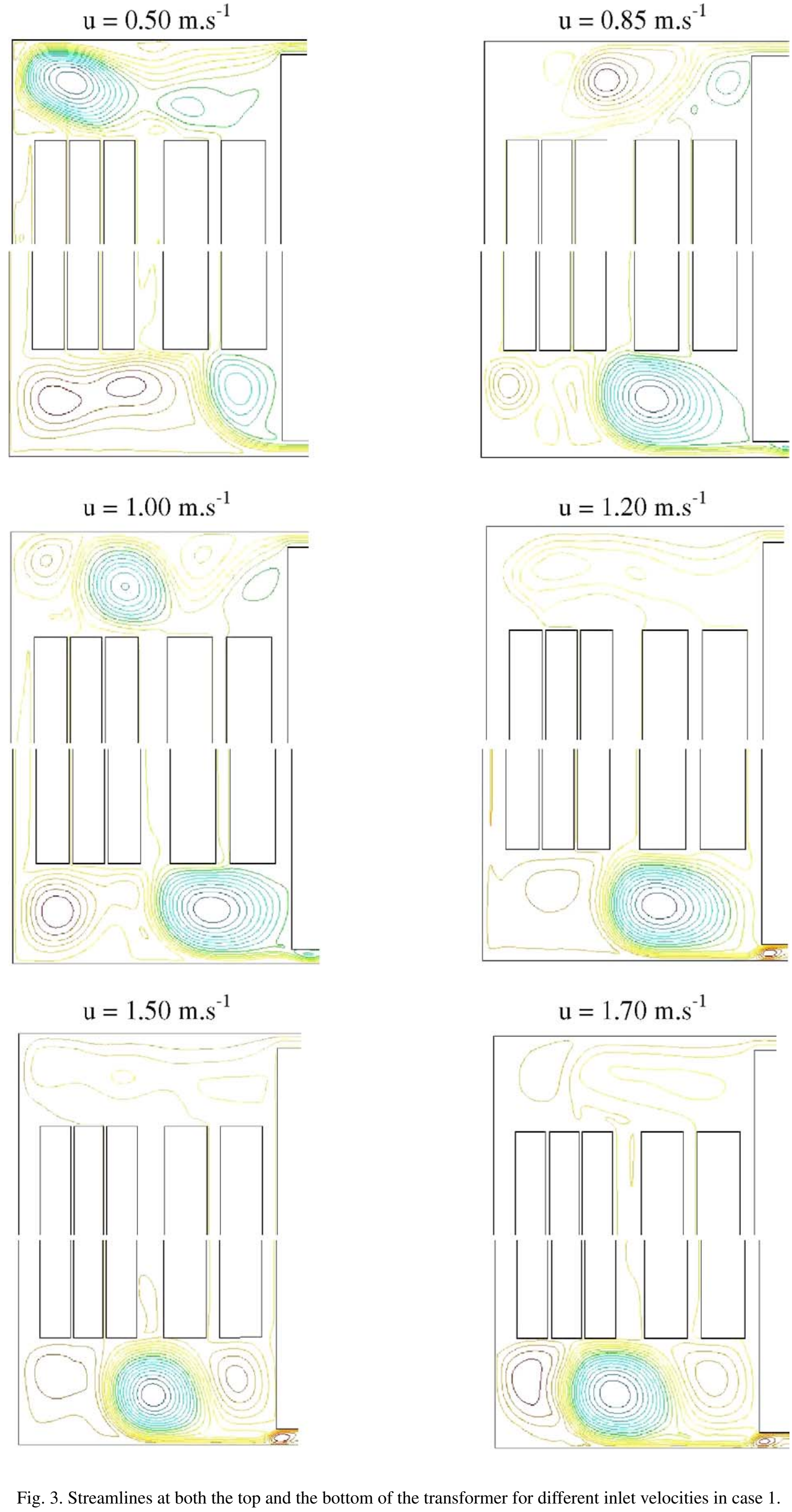

Fig. 3. Streamlines at both the top and the bottom of the transformer for different inlet velocities in case 1.

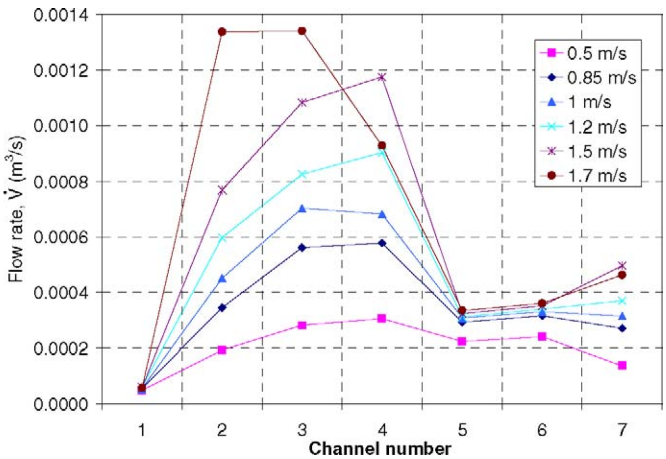

Fig. 4. Volume flow rate in the different transformer channels for the case 1.

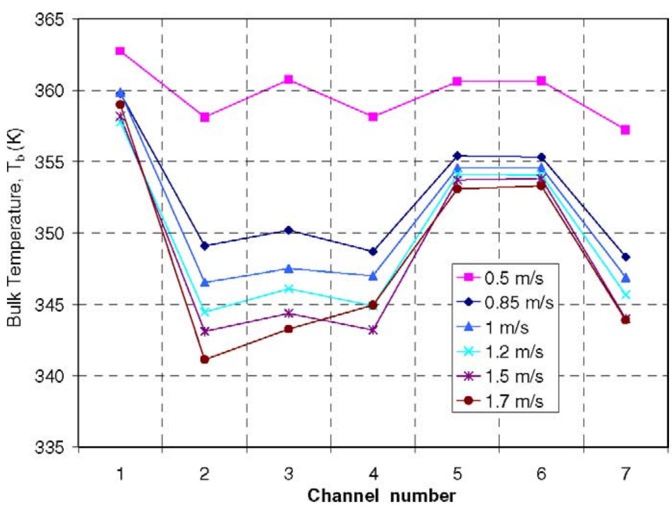

Fig. 5. Bulk temperature in the different transformer channels for the case 1.

est surface temperature is located at the cooling channel walls inside the secondary windings where the heat flux is biggest (Fig. 6).

By increasing the inlet velocity, we can observe that the flow rate will increase rapidly in the first larger channels near the entrance, because under the pressure at the entrance, the fluid will search the nearest issue to be evacuated. We can observe a big roll under the secondary windings which will force the fluid to go into the cooling channels leading to a decrease of the wall and bulk temperatures (Fig. 5) in the channels 2, 3 and 4. On the other hand, we can observe that the hot fluid going out of the cooling channels flows near the top surfaces of the transformer tank before its exit. This will not allow a good mix of the fluid and some cold region can be observed there (Fig. 2).

4.2. Case 2

In the second case, the use of insulations at both the top and the bottom of the windings reduces the space for the fluid flow. Moreover, the insulations limit the contact between the fluid and the bottom of the windings; consequently, the fluid absorbs

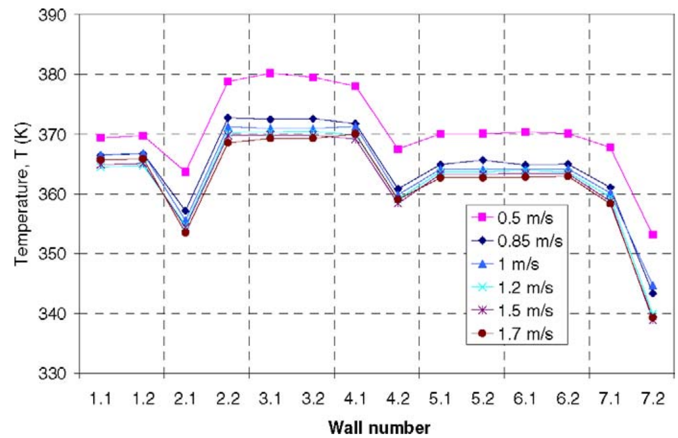

Fig. 6. Highest wall temperature in the different transformer channels for the case 1.

less heat than in the previous case at the bottom of the transformer.

For low inlet velocity the fluid flow rate is nearly the same in the different channels (Fig. 8) and the maximum wall temperatures are greater than case 1 because the heat flux is bigger in the channels by eliminating the contact of the fluid with the top and bottom of the windings (Fig. 10).

The streamlines in Fig. 7 show that the rolls are not very strong and the maximum flow rate is located in channel 4 which separates the two windings. This difference of the flow rate with other channels becomes very big in the case of maximum inlet velocity at 1.7 $m \cdot s^{-1}$ leading to a decrease of the bulk temperature in this channel (Fig. 9). But what we need is to reduce the temperature in the cooling channels crossing the windings.

At the top of the transformer, we can observe that the rolls are very weak, and the fluid that exits the channels will go directly to the exit of the transformer. However, that going out of the primary cooling channels flows near the top wall of the transformer tank before going out. This will reduce the mixing of the fluid and some cold region remains inside the fluid (Fig. 7).

4.3. Case 3

The use of longitudinal cylindrical insulations in both separating channels core/secondary windings and primary/secondary windings reduces their width by dividing them by two. On the other hand, the presence of a large space under the secondary windings with an obstacle (the cylindrical insulation) enhances the flow through the cooling channel (channel 3) inside the secondary windings (Fig. 12).

Fig. 11 shows that at the top of the transformer there are many strong rolls over the windings as well as under them. The movement of these rolls is aided by the presence of the obstacles creating a special space for the rolls. These rolls give a good mixing of the fluid and consequently its temperature becomes more homogeneous at the top of the transformer (Fig. 11). On the other hand, we can observe that the cooler regions are located near the insulations.

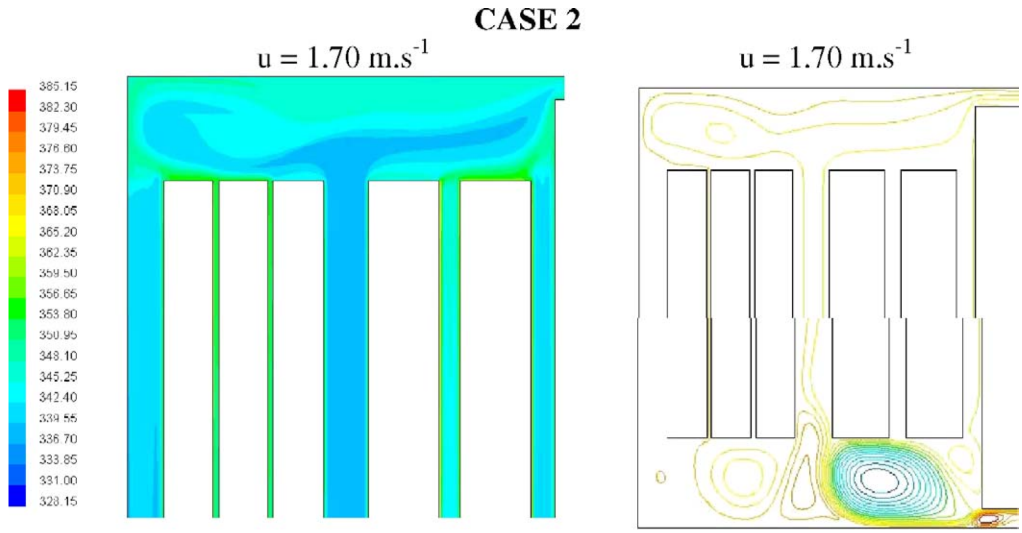

Fig. 7. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 2.

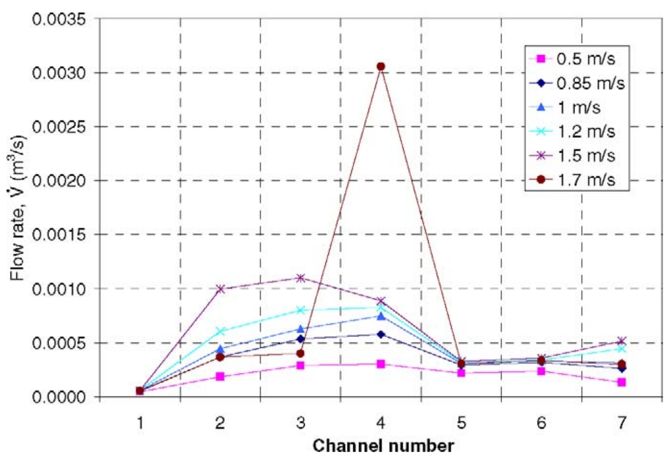

Fig. 8. Volume flow rate in the different transformer channels for the case 2.

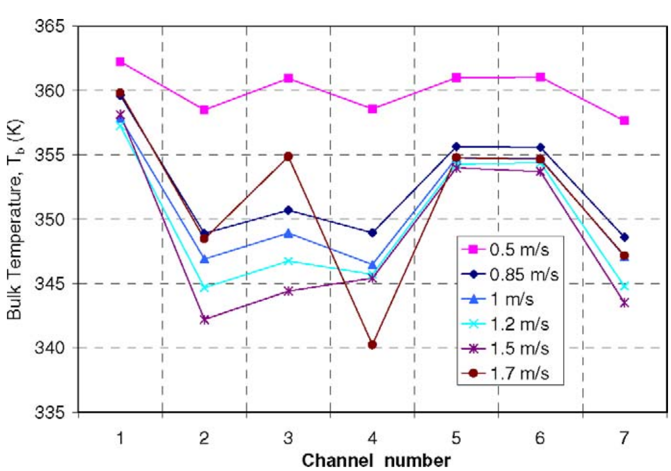

Fig. 9. Bulk temperature in the different transformer channels for the case 2.

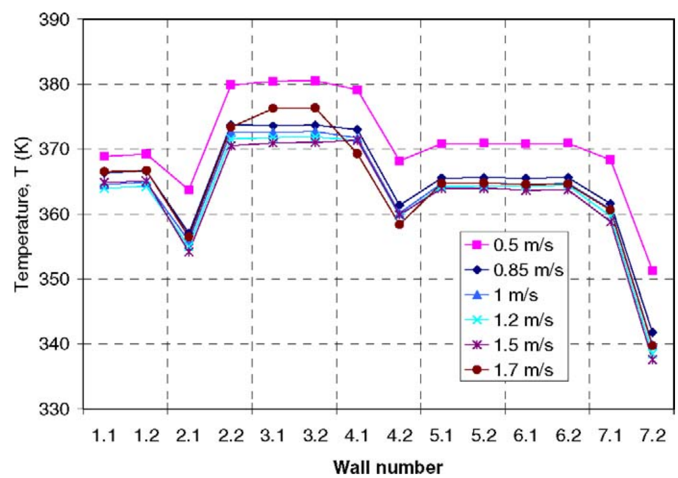

Fig. 10. Highest wall temperature in the different transformer channels for the case 2.

With increasing inlet velocity, the pressure at the entrance will propel a part of the fluid behind the obstacle to flow through the last channel as well as through channel 4b situated just behind the obstacle, the flow rate in these channels will increase rapidly (Fig. 12) leading to a decrease of the bulk temperature (Fig. 13) without any important change of the highest wall temperature (Fig. 14).

4.4. Case 4

In the case 4, the space reduction with the presence of the insulations on both the top and the bottom of the windings and the absence of obstacles allow for low inlet velocity to have nearly the same flow rate in the different channels (Fig. 16). In these cases, many rolls are formed at the top and the bottom of the transformer which will lead to good homogeneous temperature in these parts of the transformer.

With increasing inlet velocity, the favorite channel will be channel 3 which is the first large channel near the entrance and where the flow is aided by natural convection because of the big heat energy generating inside it (Fig. 16). But for higher inlet velocities like 1.5 $m \cdot s^{-1}$ and 1.7 $m \cdot s^{-1}$, the roll under the secondary windings will move toward the insulation and the fluid

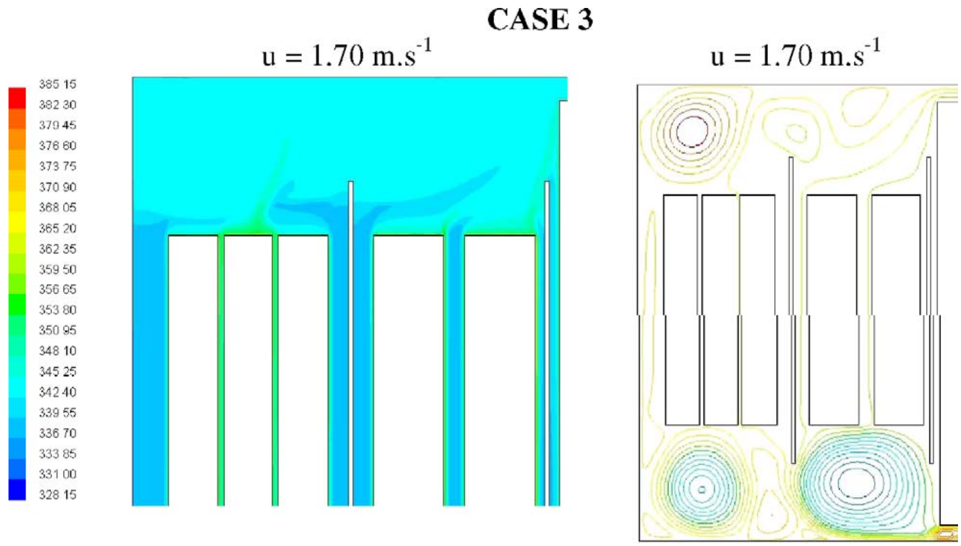

Fig. 11. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 3.

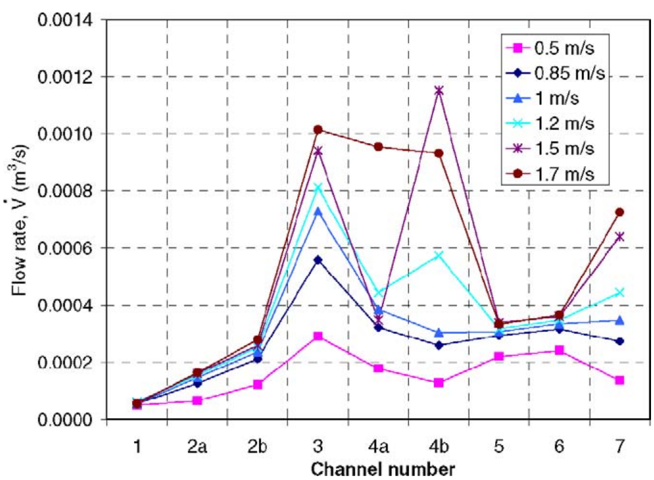

Fig. 12. Volume flow in the different transformer channels for the case 3.

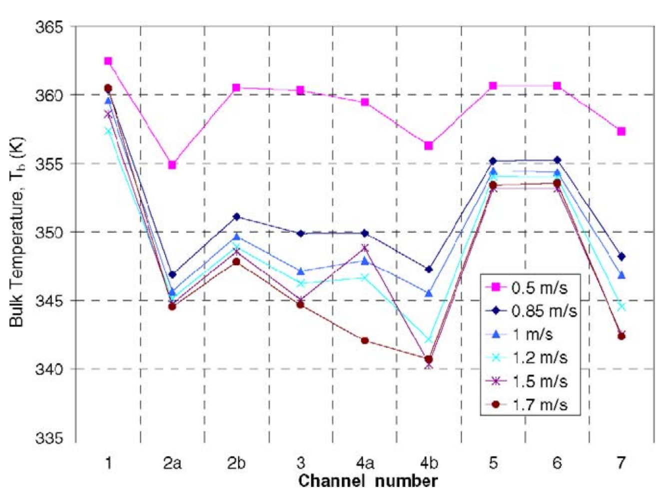

Fig. 13. Bulk temperature in the different transformer channels for the case 3.

will flow more easily in channels 4 especially in channel 4a (Fig. 16) leading to a decrease of the bulk (Fig. 17) and highest wall temperatures (Fig. 18).

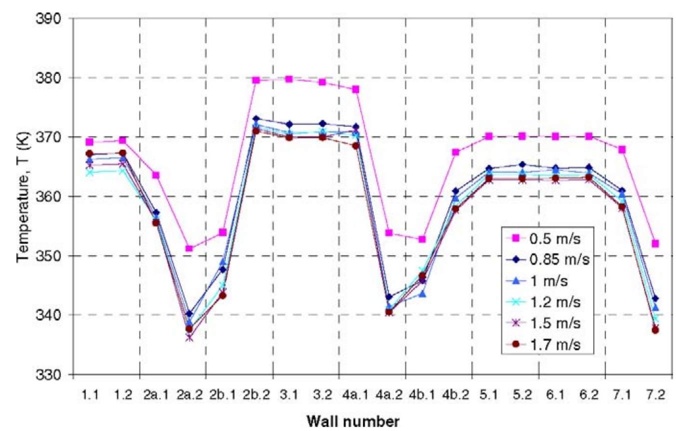

Fig. 14. Highest wall temperature in the different transformer channels for the case 3.

Fig. 15 shows that for high inlet velocities, the fluid going out the channels behind the insulations flows near the top wall of the transformer tank before the exit. But, the fluid going out the other channels will choose the direct way to exit. Consequently, we can observe a cool layer of fluid remaining at the center part of the top of the transformer bounded by two hotter ones.

4.5. Case 5

The use of double longitudinal insulations in the channel separating the primary and secondary windings and that one separating the secondary windings from the core reduces the width of these channels and makes the flow difficult through them. On the other hand, the absence of the insulations under the windings with the presence of obstacles (the longitudinal insulations) divide that space in two parts allowing the creation of rolls where the fluid will be in contact with the hot bottom walls of the windings (Fig. 19). The fluid absorbs heat energy and flows through the cooling channel inside the secondary windings aided by the convection heat transfer, because this channel

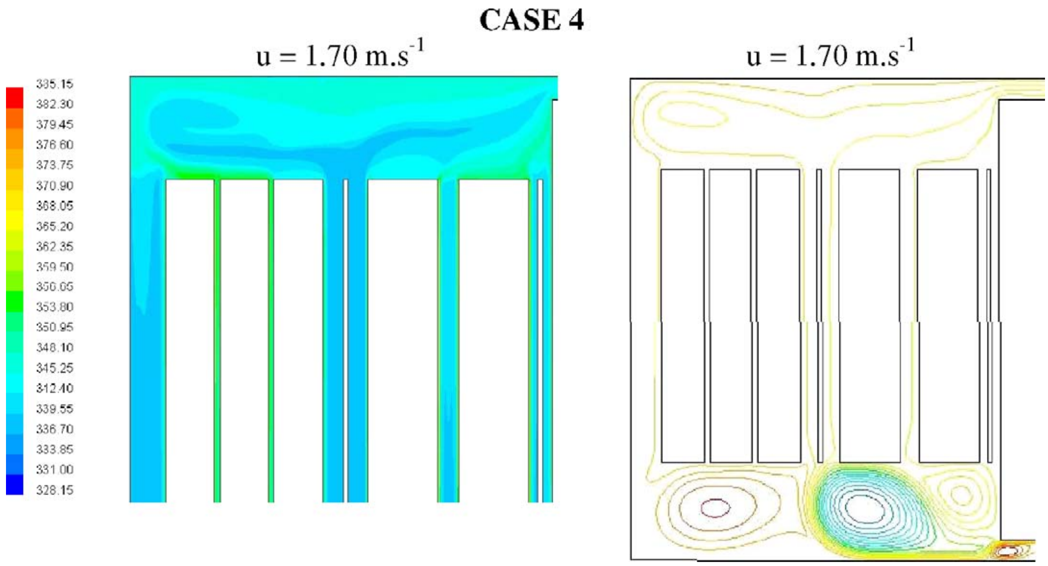

Fig. 15. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 4.

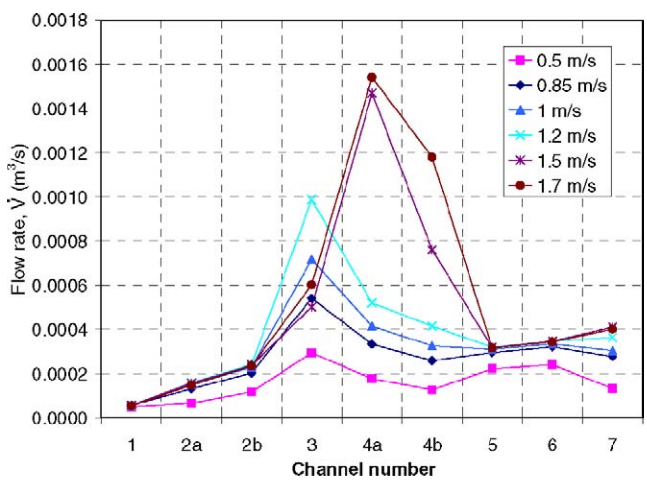

Fig. 16. Volume flow rate in the different transformer channels for the case 4.

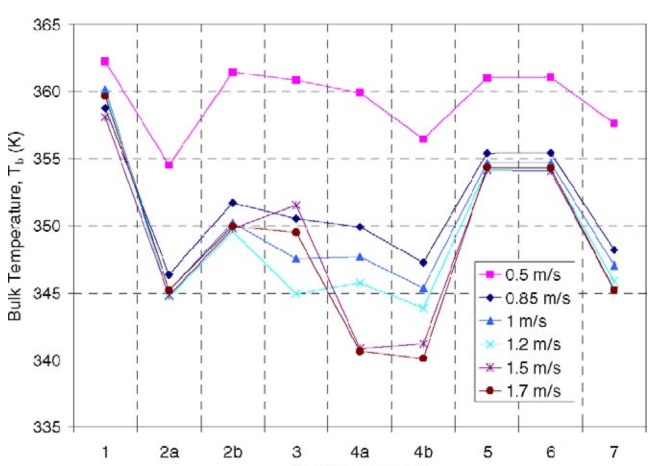

Fig. 17. Bulk temperature in the different transformer channels for the case 4.

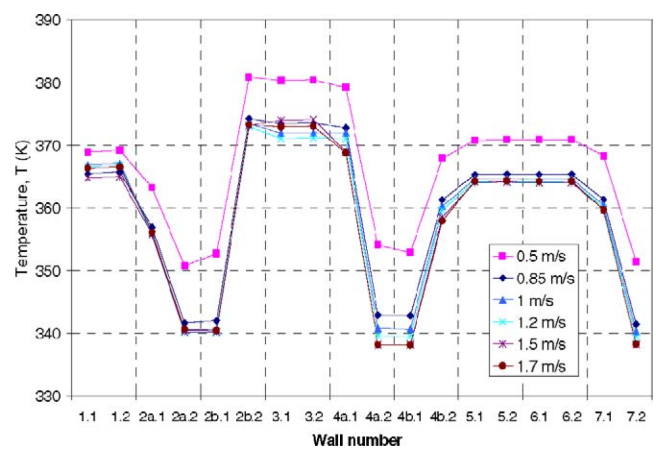

Fig. 18. Highest wall temperature in the different transformer channels for the case 4.

has two heating surfaces but the other ones in the separating channel have only one (Fig. 20). On the other hand, we can see that there is no flow in the channels between the insulations (2b and 4b), this is because the channels are narrow and there is no natural convection inside them. The highest wall temperature is located in channel 2c (Fig. 22) despite the fact that it has the same width and nearly the same bulk temperature as channels 5 and 6 (Fig. 21) because it has only one heating surface where the others have two.

For low inlet velocities the temperature of the fluid at the top of the transformer is nearly homogeneous due to the presence of rolls leading to a good mixing of the fluid. With increasing inlet velocities, the flow rate increases rapidly in the channel 3 then in those around the primary windings, but it remains nearly constant in the other channels. For higher velocities, we can see that the fluid going out the channels goes directly to the exit without turning in rolls.

4.6. Case 6

In this last case with insulations at the top and the bottom of the windings and the absence of the obstacles, the channel 3 remains the preferred one for the flow at low inlet velocities. But

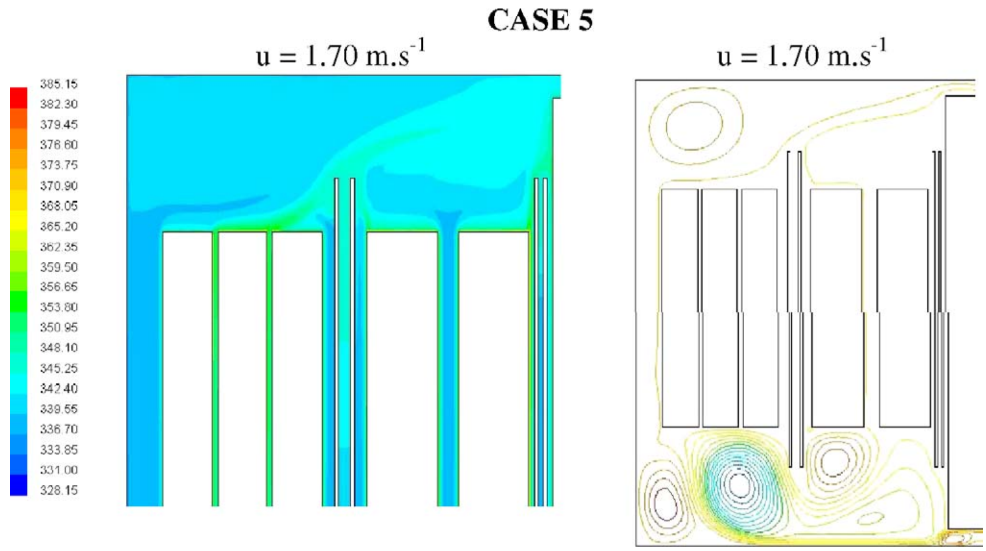

Fig. 19. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 5.

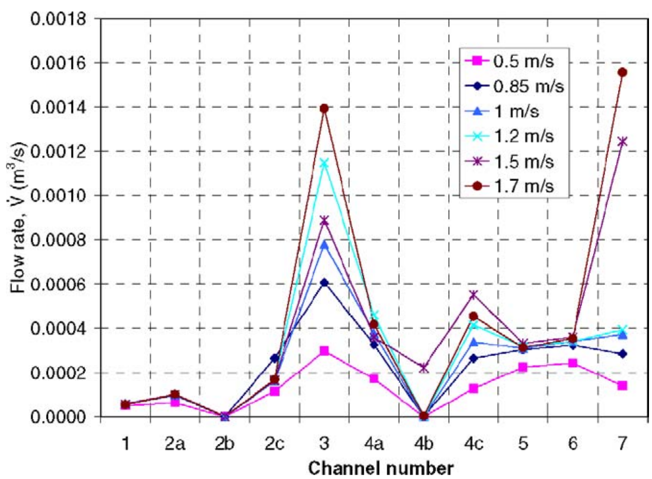

Fig. 20. Volume flow rate in the different transformer channels for the case 5.

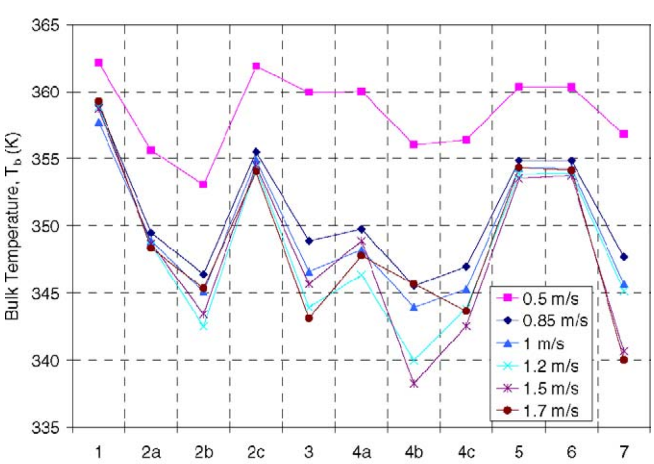

Fig. 21. Bulk temperature in the different transformer channels for the case 5.

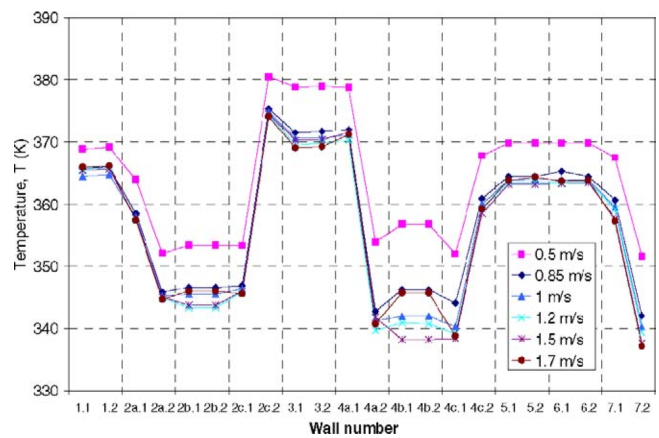

Fig. 22. Highest wall temperature in the different transformer channels for the case 5.

with increasing inlet velocities, the absence of heating by the bottom of the windings and under the pressure at the entrance the fluid chooses channel 4a and for the highest velocity it is propelled to the last channel (Fig. 25) which leads to a decrease of the bulk temperature in this channel (Fig. 26). Moreover, a flow appears in channel 4b between the two longitudinal insulations.

Fig. 23 shows the presence of many rolls at the top of the transformer for the low inlet velocities leading to a good mixing of fluid and consequently to nearly homogeneous temperature. But these rolls will vanish with increasing velocities and the fluid outgoing the channels will go directly to the exit.

The highest wall temperature is located at the surface of the secondary windings in channel 2c (Fig. 27), this is due to the effect of the presence of the longitudinal insulation which reduces in the same time the width of the channel and the heat natural convection leading to a small flow rate and consequently to a high temperature. Moreover, we can observe that this temperature is bigger than the other cases.

4.7. Comparison

As expected, the numerical results give the highest temperature on the secondary windings surface. Fig. 28 shows that with

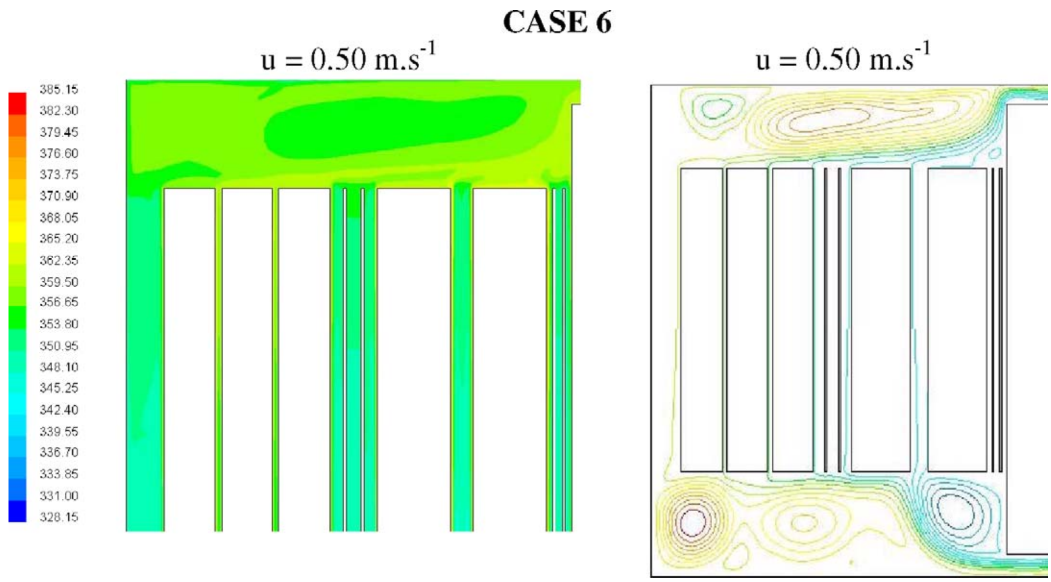

Fig. 23. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 6.

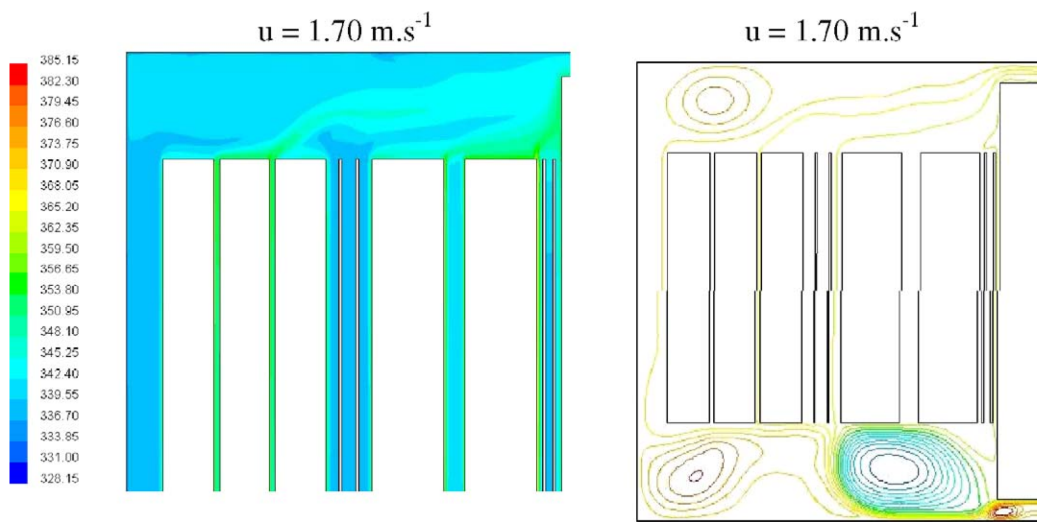

Fig. 24. The isotherms plots at the top of the transformer and the streamlines at both the top and the bottom in case 6.

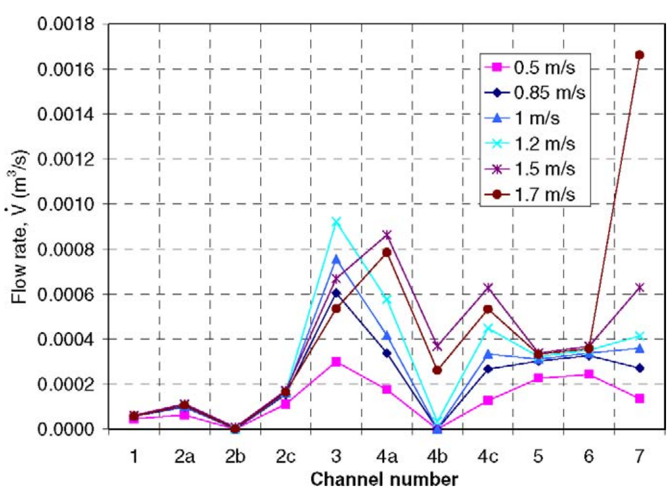

Fig. 25. Volume flow rate in the different transformer channels for the case 6.

increasing inlet velocity the maximum surface temperature inside the cooling channel of the secondary windings decreases. For low inlet velocities less than 0.85 $m \cdot s^{-1}$ the maximum temperature outgoes the authorized limit, so higher velocities are needed. On the other hand, high temperature is also located at the top of the secondary windings because the fluid there is very hot and has a little motion; so to reduce this temperature, the inlet velocity must be equal or greater than 1.70 $m \cdot s^{-1}$.

The comparison of the different cases in Fig. 29 shows that the basic case gives the better results because the cover insulations on the top and the bottom of the windings reduce the contact surface with oil and therefore increase the heat flux inside the cooling channels leading to higher maximum temperature.

For all cases we can observe that with increasing inlet velocity the fluid under pressure will search the first wide way to exit, therefore it flows through the cooling channel in the sec-

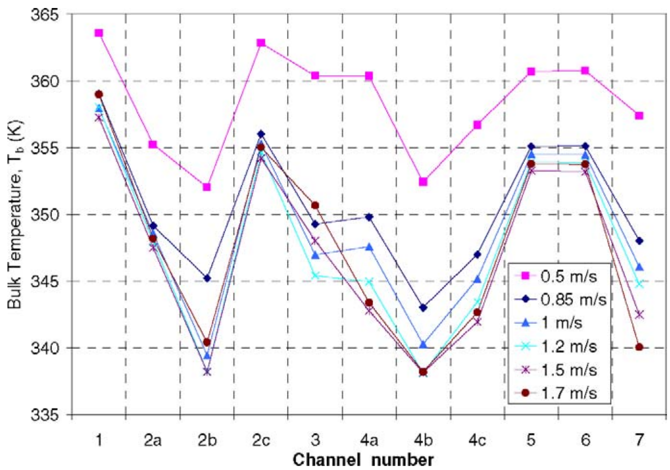

Fig. 26. Bulk temperature in the different transformer channels for the case 6.

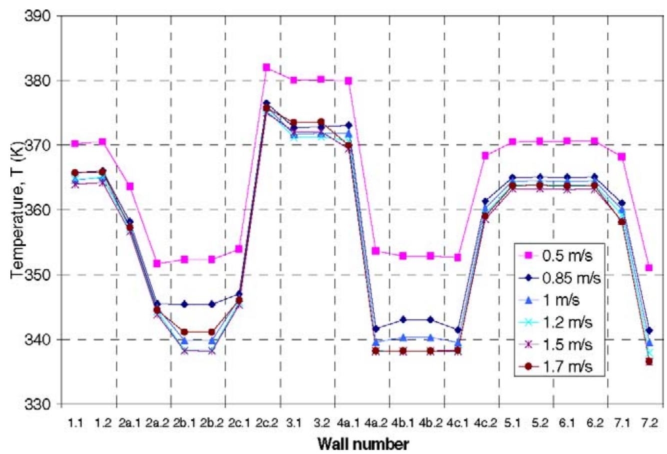

Fig. 27. Highest wall temperature in the different transformer channels for the case 6.

ondary windings (channel 3) aided by the natural convection and some rolls at the bottom of the transformer tank. In this manner the flow rate will increase in this channel leading to a decrease of the bulk temperature. The hot mineral oil outgoing this channel is flowing along the tank top wall before leaving the transformer without a good homogenization of the temperature. For this reason, the fluid cannot reach easily the cooling channels in the primary windings, which leads to a little change in the volume fluid flow rate and consequently to a stabilization of the bulk temperature in this channel which remains without noticeable change.

5. Conclusion

The heat transfer and fluid flow inside the oil-cooling channels of transformer is somehow complex and reverse flow can appear. The best geometry configuration is the first case without insulations. If the reverse flow is better for the oil temperature homogeneity and if it can contribute to heat transfer by evacuating the heat from the transformer windings and core, it seems that a directed flow can give better results. The hottest temperature of the windings surfaces is located inside the cooling

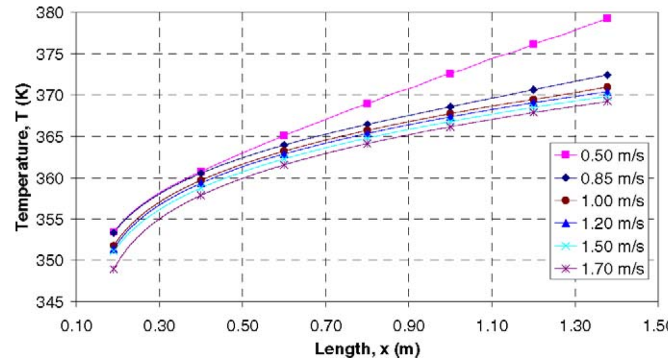

Fig. 28. Temperature profiles along the wall of the cooling secondary windings channel for the case 1 at different inlet velocities.

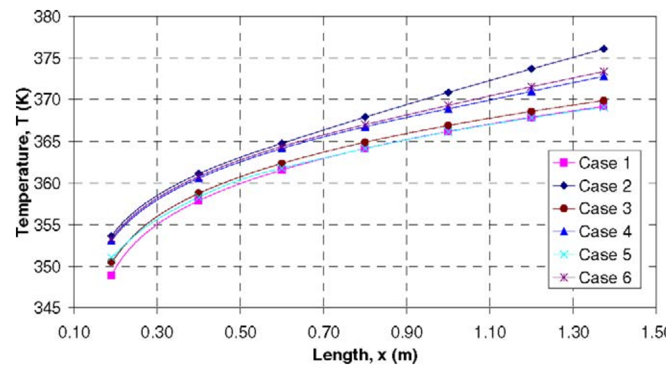

Fig. 29. Temperature profiles along the wall of the cooling secondary windings channel for the different cases at the inlet velocity $u = 1.70\ \text{m}\cdot\text{s}^{-1}$.

channel of the transformer secondary windings, but the higher mineral oil bulk temperature is located in that of the transformer primary windings which are narrow and far from the entrance. The inlet velocity of $1.7\ \text{m}\cdot\text{s}^{-1}$ seems to be the good choice for cooling the transformer because it allows a good decrease of the secondary windings wall temperature which is a critical problem of the transformer. Higher inlet velocity increases costs without any certitude of better results due to the complexity of the geometry. In the future, it is interesting to study the effect of the use of thermal source inside the windings and the core.

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