Investigating Characteristics of N_2, CO_2 and CF_3I in Contrast to High Current Arcs in Circuit Breakers to Choose a Suitable Substitute for SF_6

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Abstract: Specific and sensitive operation of circuit breakers makes an individual position for them in power networks. Circuit breakers are at the central gravity of variations and execution operations. Therefore, an optimum operation is the main reason to investigate about new gases to be used in MV and HV circuit breakers instead of SF_6. The arc process has enormous complexity because of hydrodynamic and electromagnetic combination equations, and that is the exact reason why most of the previous simulations were processed in two-dimension analysis. But, in this paper a three-dimension simulation with sufficient resultshas been fully discussed. Different evaluations on the other gases have taken under study in order to find a suitable substitute instead of SF_6 gas, which can also bring an optimum operation for the breakers and can be even friendly with the environment. The simulations have been carried out based on the finite element method (FEM) and magneto-hydrodynamic equations. A three-dimension model under the transient state has been chosen in the simulations to find a feasible substitute for SF_6 gas. The main factors of the analysis are threefold as follows: arc temperature on the different regions, the cooling ability and arc resistance. CO_2, CF_3I and N_2 are nominated to substitute the SF_6 gas and their effects on cooling ability, nozzle evaporation, contacts erosion and arc resistance will be discussed.

Keywords: Magnetohydrodynamic (MHD) Equations, Finite Element Method (FEM), Cooling Ability, Substitute Gas.

1. Introduction

SF_6 has been used in circuit breakers to extinguish arc during operations and in zero current time. High transferring heat properties and appropriate insulation resistance-have made sulfur hexafluoride to be used almost exclusively in gas power switches [1, 2].However, researchers have got some issues to substitute the SF_6 gas in circuit breakers. From the top of these arguments, the environment concern can be considered and also the better operations such as: reduction of effective heat and chamber corrosion, are as interest [3-5]. Sulfur hexafluoride has some other side effects and has been known as a greenhouse gas based on the high infrared attractions, long life time in environment and recombination with oxygen.In recent years, other fluids such as CO_2, CF_3I and N_2 have been clarified in terms of heat conduction, electrical conductivity and even viscosity, accompanying the variation of pressure and heat [3].

Comparing to SF_6, CO_2 has got lower insulating powerand it has been almost always known as a greenhouse gas, but however, the researchers have become to conclusion that the CO_2 can be substitute with the SF_6 gas, because of its higher dielectric property and electronegative characteristics [6-10]. The CF_3I can hence be of interest to perform as a breaker insulator.Here are some explanations for this pretense in terms of comparing CF_3I with SF_6:

1. Dielectric power compared to SF_6 gas is the same
2. Lower global warming potential
3. Higher molecular stability

In previous researches, the analyses of substitutionary gases have carried out only by the theoretical data. In this paper, a 3-dimensional simulation has been accomplished in order to study how accompany of varying and different gases can be forced on the arc impact, and also the regarding results from the gases characteristics analysis are used,

in addition.

Studying arc in a 3-dimension simulation is one of the most complex issues in plasma physics. Most likely, arc phenomenon is simulating with finite element method (FEM), which in this paper the same method is being used in order to processing the arc impact from diverse gases.FEM settings in the whole process are as follows:

1. Defining circuit breaker geometry
2. Setting boundariesand initial conditions
3. Selecting equations and importing functions proper to arc process
4. Setting solvers and time steps ofsimulation under transient state
5. Running and solving the equations

To modeling the arc impact in 3-dimensions, all the system rulings equations and their solving algorithms must be executed properly. As a response to the latest argument,the simulations have been carried out based on the magneto-hydrodynamic (MHD) equationsand the arc 3-dimensions solving algorithms are assumed as it is discussed in [18]. The method discussed in [18] is actually recorded the arc impact with high speed camera, and the results are taken into account with the simulations which guaranties the solvation method.

When analyzing a whole system in a limited territory is of a matter, there is no need to simulate the whole geometry structures all in together. Just the effective and influenced phenomena would be enough to take into accounts in the simulations.To do so, only the nozzle, chamber, contacts, and the inlet/outlet fluid pores are assumed in the simulations. As a result, the procedure execution time, and simulation size are reduced and also it's a faster convergence product.

One of the basic items that have to be obtained in the simulations process is the fluids characteristics. Using hydrodynamic and electric characteristics of the fluids makes it easier to simulate the fluids impact on the arc [3].The fluids that are discussed in this article are: CO_2, CF_3I ,and N_2, whichwill be compared to each other individually and also to SF_6.

Assuming all the above mentioned items, in this paper, the fluids action in contrast with high current arcs will be discussed which can complement the previous studies.

2. System Ruling Equations

The relation between the arc current, magnetic field, and plasma flow are shaped in the form of magneto-hydrodynamic equation which is in relation with k-ε turbulence model [11,14] in which k and ε are turbulence kinetic energy and loss ratio. The k-ε model has been applied most of the times for modeling the plasma arc [13-15, 17-20]. In addition to k-ε model, other parameters like arc current distribution in 3-dimensions and self-magnetic field have

to be calculated as well.The solution to arc current distribution can be expressed along the ohms' law and can be calculated from the continuity equation ($\nabla .j=0$). The self-magnetic fieldcan be derived from the ohms' law by applying the magnetic potential field calculation.

The time related equations are described via mass conservation law, momentum conservation law, mass transferring via energy conservation law, and momentum and plasma flow energy.

Radiation is one of the important phenomena which can make the energy transferring system possible in arc plasma system [21].The radiation linkage flux in a specific situation is a function of local properties, pressure and temperature.The absolute conductivity coefficient is used in most of the studies in order to calculate the arc phenomenon radiation [22], which is a validate result, so this method is nominated to simulate the radiation linkage flux.

A standard k-ε model is used to simulate the turbulence effect which is produced by arc and fluid. Variable parameters k and ε are related up to their own equations.

In analyzing the fluids, the heat transferring ability is in process to choose a suitable substitute from the heat transferring equations. Nevertheless, knowing that convection plays the key rule in heat transferring, Newton's law of cooling is considered as follows:

$$q=hA(T_w\text{-}T_f) \tag{1}$$

where A is the connection surface area, T_w-T_f states the temperature difference between the fluid and the heat source, and h is the convective heat transferring coefficient. Normally, Newton's law of cooling states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings. As such, it is equivalent to a statement that the heat transfer coefficient, which mediates between heat losses and temperature differences, is constant. From the given statement, it becomes obvious that the bigger surface area and higher temperature differences between the fluid and the heat source are, the more heat transfer is.In this paper the arc impact is well-defined and considered as the heat source. In addition, focusing on the other heat transferring impacts as describes below leads to an expert study:

1. Fluid physical properties: heat capacity, density, thermal conductivity coefficient, and viscosity in which the thermal conductivity coefficient is proportional to the heat conductivity.
2. Fluid motions
3. The geometry shape

All the mentioned factors influence the convective heat transferring coefficient.

The fluid floating in breakers is a conclusion of the con-

tact movement and the piston below it, which is a compulsionreaction.In this paper the fluid inlet velocity is assumed as 1 m/s. in the same condition, the convective compulsion coefficient is always bigger than the natural convective coefficient, which can differs more than 100 times. The Newton's law of cooling says that h is not proportional to the temperature, but it is only true in compulsive convection coefficient under specific conditions, where in fact h is proportional to temperature difference (ΔT) with a function to the power of 1/3 up to 1/4.

3. Simulations

In order to evaluate the operation quality of a fluid in circuit breaker for the mentioned fluids, a breaker with its structure characteristics has been chosen as a case study with voltage of 33 kV and 1250 A, where the simplified system is depicted in Fig. 1. The arc conductive parameters such as: electrical conductivity, specific heat capacity, dynamic viscosity, fluid density and thermal conductivity are proportional to pressure and temperature based on the gases individual properties.Transferring coefficients that are concluded from previous operational and theoretical studies [3, 16] are used as assumption in the simulations. Based on the described equations on section 2, and also the magneto-hydrodynamic equations, all the calculations are fully considered in finite element method (FEM) [17-20]. There is also a notation of alternative arc current amplitude which is assumed up to 10000A (50 Hz) and also some initial conditions as follows:

Fluid initial temperature of 300K, and initial pressure of 0.35Mpa

The amount of temperature is known as an importantvalue for the arc parameters and as an influence on physical properties. Temperature in different chamber areas has
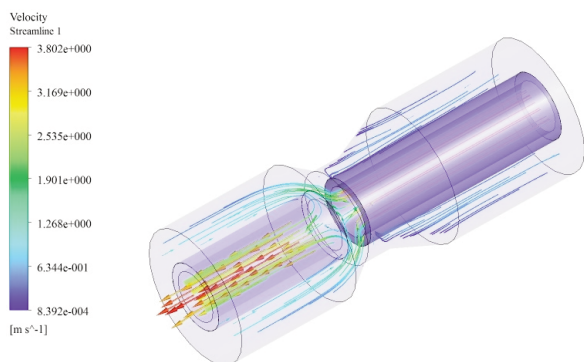

Fig. 1. The case study and fluid motion paths during the operation
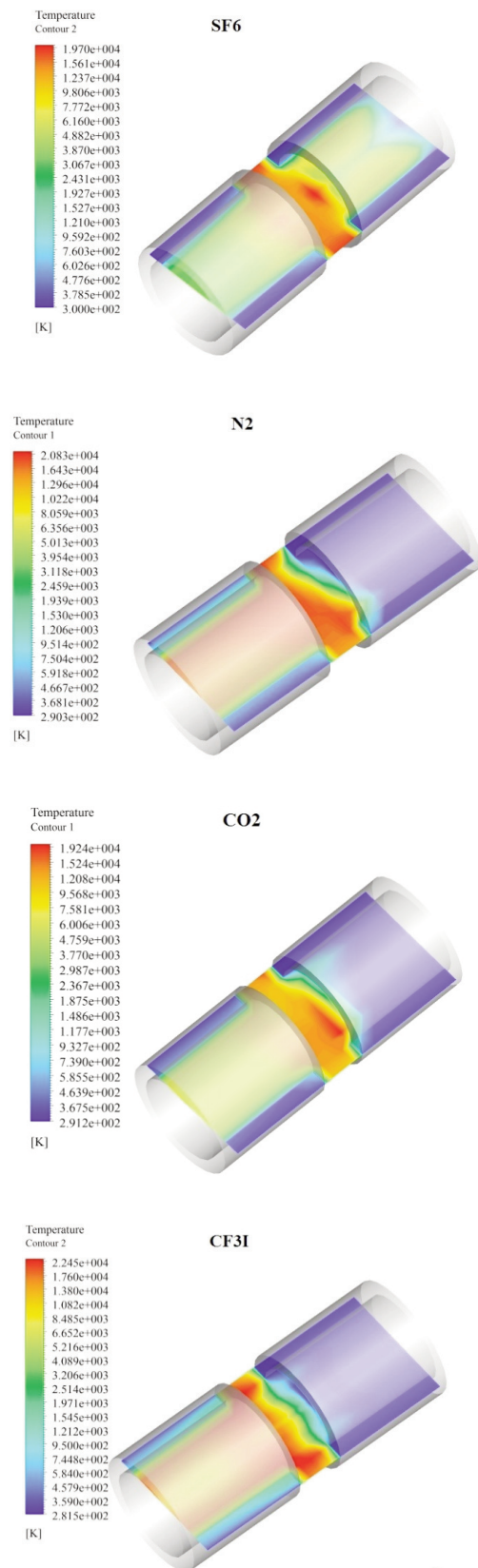

Fig. 2. Thermal distribution between contacts in 5ms

also impacts on arc current distribution, arc resistance, and fluid physical properties (such as thermal conduction and viscosity). So, if the arc temperature can be reduced, it results on better breaker operation. Lower the arc temperature is, better the breaker operation is attached.

The arc simulations for all mentioned fluids have been taken into the case study with the same condition respect. The main result of the fluid physical properties effect on their temperature during the first half period and thermal distribution in contacts region for different fluids is depicted in Fig. 2(in 5ms). Maximum amplitude of current occurs in 5ms and temperature at this time is highest almost always. This process can create an option in which the different fluids can be compared during the maximum temperature in arc time. In Fig. 2. maximum temperature occurs respectively in CF_3I, N_2, CO_2 and SF_6 eventually. Considering the lowest temperature that shows up in SF_6, it seems as if this fluid can operates betterthan the others. This is mainly because of the higher thermal conductivity of SF_6 in lower temperatures, and suitable molecular mass and higher specific heat capacity in temperatures between 15000K up to 30000K. Each specific fluid, reaches its maximum thermal conductivity in a known temperature valley. Considering the conductivity amount in reference [3], CF_3I in the temperature valley of 2000K up to 3000K has higher thermal conductivity than CO_2 and N_2. CO_2 and N_2 have higher thermal conductivity than CF_3I in the temperature range of 6000K up to 10000K. Highest thermal conductivity refers to SF_6 in temperature range of 1000K up to 2500K.

In temperatures more than 16000K, the highest thermal conductivity refers to SF_6 again. Higher thermal conductivity in lower temperatures is the cause of diffusion and thermal energy transferring, so, it brings decentralization in strict limits (as it is shown in Fig. 2. The thermal distribution in contacts region for is higher than the other fluids, and larger amount of the fluid concerns in the heat transferring process.)

Based on the higher molecular mass which is refers to CF_3I, it gets higher thermal conductivity in a reasonable temperature valley, and therefore it is expected to operate just like SF_6 when it becomes to meet the arc. However, CF_3I in temperature ranges bigger than15000K has lower thermal capacity and as a result its temperature gets higher with lower amounts of energy. In the mentioned temperature valley, CO_2 and N_2 have reasonable thermal capacity, but their lower molecular mass decreases the heat transferring a little bit.

Varying viscosity during the operation causes a limitation in fluid motion transferring at the arc boundary. Lower viscosity increases the fluid cooling ability and decreases the arc temperature during interruptingarc process. The viscosity of CF_3I, N_2 and CO_2 is lower than SF_6 which is one of the benefits of the 3 mentioned fluids. The fluids highest viscosity happens in temperature valley from
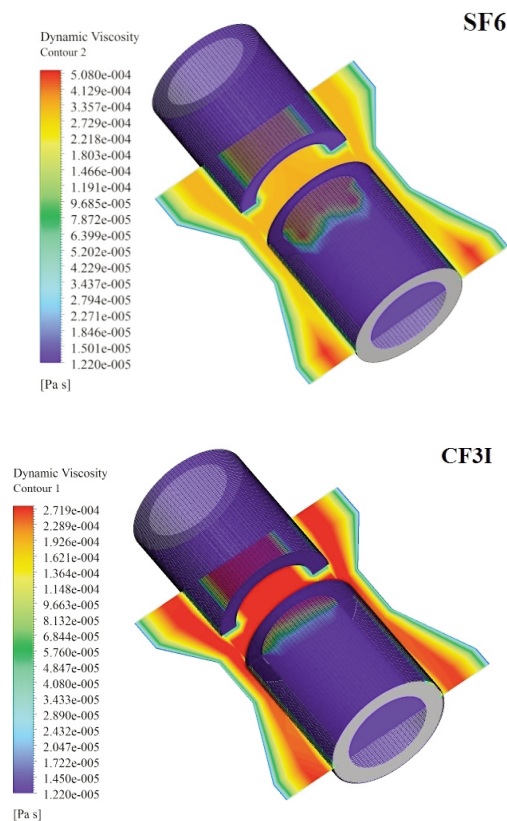

Fig. 3. Viscosity of and CF$_3$I in zero current time (or 10ms)

7000K up to 15000K. In temperature valleys of 300K up to 7000K and 17000K up to 30000K, CF_3I and SF_6 viscosity almost coincides on scheme which means the viscosity amounts of these two fluids are so close, but in temperature valley of 7000K up to 17000K, CF_3I gets lower position than SF_6 on the scheme and it is expected to have a better cooling impact than SF_6. However, this differential issue is not enough to recompense the lower heat capacity of the CF_3I (In Fig. 3 the viscosity of the two fluids CF_3I and are shown).

The CF_3I viscosity is lowerin amounts which coincides the previous discussion.The average viscosity in the selected region for CF_3I is 1e-4 and for SF_6 is 1e-5. In the case of the two other fluids, this point is a little different, and their viscosity compared to SF_6 have a noticeable dissimilarity, therefore they have improved cooling condition. Especially CO_2 which is the lowest viscosity, threats in a similar manner as SF_6.

This argument can be fully discussed when maximum temperatures in arc channel are considered for different operation times (arc channel usually occurs between two contacts), therefore the fluids maximum temperature variations are curved in Fig. 4.
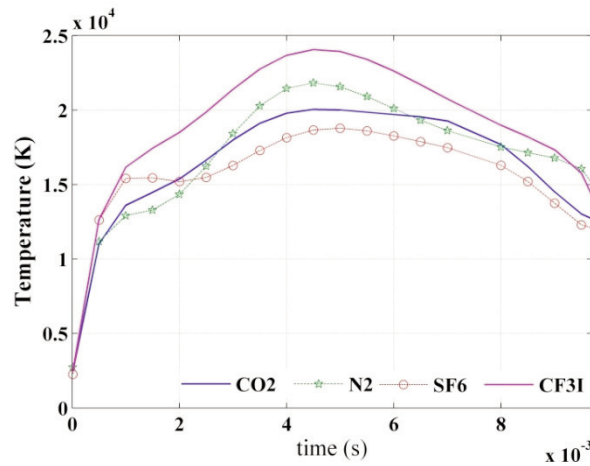
Fig. 4. Maximum temperature between the contacts (in arc channel), during the arc

The result is similar to the previous conclusions where the lowest amount in maximum temperature for different operation times refers to SF_6 and CO_2 is the second ideal fluid in this study. The fluids cooling impact can be operated in many ways. Maximum temperature occurs in one spot or in a very limited region, so it cannot demonstrate the cooling power process alone. Therefore, the average temperature between the contacts in arc region is curved in Fig. 5 for all the mentioned fluids in half period. The results show the better operation of CO_2 and SF_6 all over again.

Temperatures rising between the contacts take place when

the arc meets the fluid directly and causes the heat convection through the whole process. Considering the fact that the nozzle is located near the arc, there is no wonder if the warmed up fluid makes it evaporate. The best fluid operation occurs when the most heat, transfers through the edges in a time duration close to current peak, and hence, average fluid temperature during the arc in nozzle region must be brief to leads into lower evaporation. Temperature distribution analysis in nozzle region and current peak time is depicted in Fig. 6. It seems CF_3I has the lowest amount in terms of heat transferring. In temperatures between 5000K up to 10000K, CO_2 and N_2 have higher thermal conductivity which show better operation in this
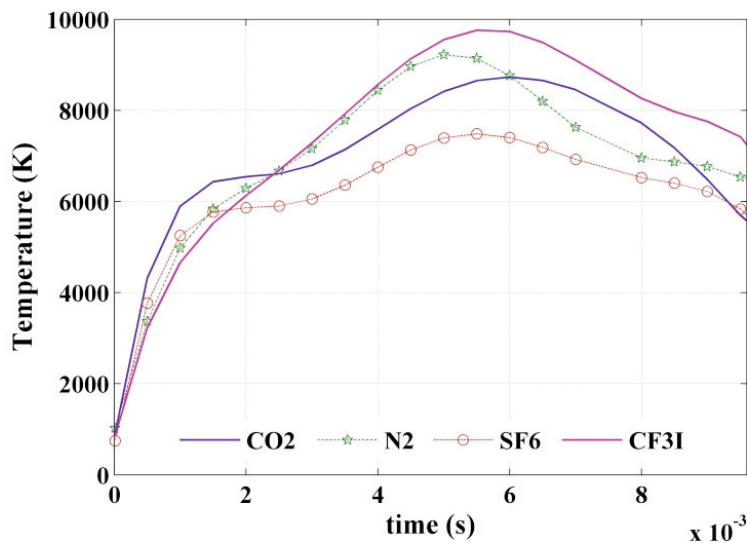

Fig. 5. Average temperature between the contacts (in arc channel), during the arc
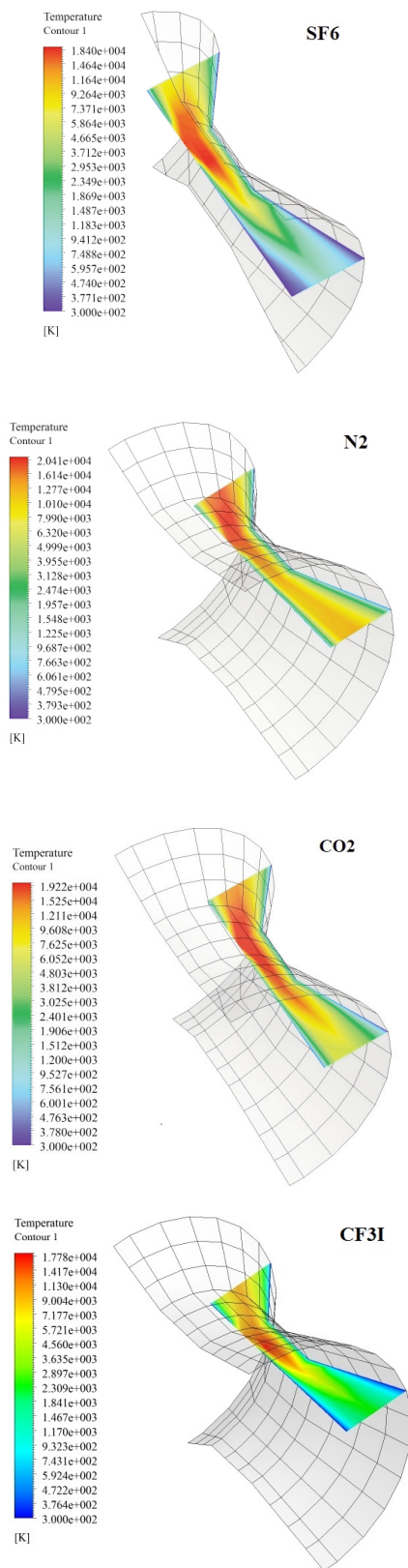
Fig. 6. Thermal distribution in the region close to the nozzle in maximum current (5ms)

manner. CO_2 and N_2 have higher heat capacity than CF_3I andthey pass through the nozzle with higher temperature that proves higher heat energy transferring by them.

In general, it is true to say which fluid that decreases arc channel temperature more has a better heat transferring and it is more succeeded to control the electric arc. Therefore, in this section, temperature rising in nozzle region is evaluated positively because it shows higher heat transferring through the arc edges in a limited space.

After analyzing heat transferring in the nozzle edges, probability and amount of the nozzle evaporation must be considered. To do this, average temperature of the nozzle region in Fig. 6 is achieved and an average temperature is calculated for the whole process. Table 1 shows the average temperature of the nozzle region through the arc impact (10ms) for all the under study fluids. According to Table 1, it is pointing higher average temperatures for CO_2 and N_2, which shows higher heat transferring through the arc edges as it was discussed earlier (this is one of the reason that reduces temperature in arc region). However, higher evaporation, nozzle corrosion, and life reduction are known as the side effects.

Table 1. Average temperature through the whole process in nozzle region

Average temperature	SF₆	CF₃I	CO₂	N₂
K	3661	4240	4693	5063

3. 1. Arc Configuration in Zero Current Time

Controlling arc and extinguishing it in zero current time is the main reason to be used fluids in circuit breakers. Electrical conductivity has a non-linear proportion relation with temperature. In most temperature valleys, temperature rising causes electric conduction to be increased and arc resistance to be decreased. The operation is more succeeded if the arc channel temperature falls in zero current time.To compare fluids and their effects on distributed current between the contacts, current density near the zero current time is depicted in Fig. 7.

Current density has been curved for 1.2e5 A/m² and even lower amounts. Current has been turned off in the case of SF_6 and there are still some current surfaces in the case of the other 3 fluids. As current density domain increases, turn-off domain can be calculated. The object poses an amount which there is no higher current density exist between the contacts. The same trend is applied for the other 3 fluids, in which the current turn-off density for CF_3I is 7e5, for CO_2 is 3e5, and eventually for N_2 is 4e5.
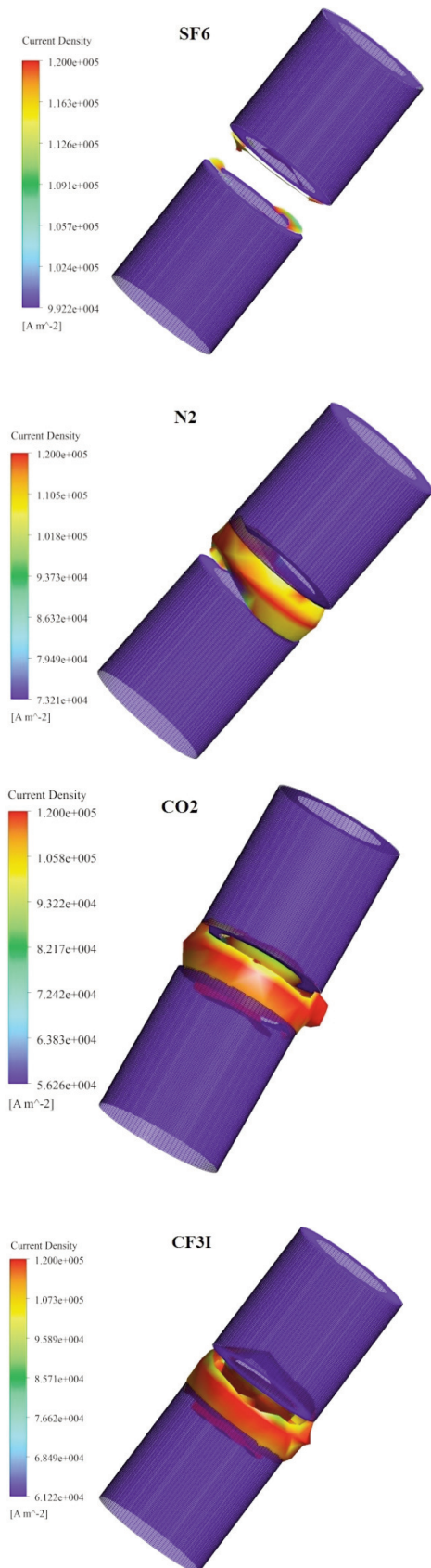
Fig. 7. Current density between the contacts for different gases near the zero current time

4. Conclusions

In order to substitute SF_6 gas in power circuit breakers, 3 basic fluids were analyzed in this paper. Then fluid characteristics were simulated in finite element method (FEM), and the results were taken out and compared from main point of view which is the temperature diffusion and current interruption time.

The average and maximum temperatures in arc region for CO_2 are close to the amount of SF_6 (in comparison to N_2, and CF_3I) and incidentally temperature distribution in CO_2 case is in a way that does not allow the temperature around the selected region for an nozzle like N_2 gets high. From the current turn-off view in moments close to the zero current, the maximum current density in CO_2 is lower than N_2, and CF_3I. According to the fluids characteristics and their operations during the arc, it seems that CO_2 has all the potential for the substitution. However, its recovery problem must be solved after zero current time, and also CO_2 molecular mass must be increased in order to increase the cooling power. To solve the latest issue, it can be recombined with heavier fluids. The two other fluids are not exempted from the very norm and their characteristics have to be modified for the use of high current electrical arc controlling. However, it seems as if they have better operation in the lower currents.

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