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DESIGN IMPROVEMENTS IN MODERN DISTRIBUTION TRANSFORMERS

SUMMARY

In the paper design improvements of distribution transformers related to improved energy efficiency and environmental awareness are discussed. Eco design of transformers, amorphous transformers, voltage regulated transformers and transformers filled with ester liquids are analyzed.

As a consequence of growing energy efficiency importance, European Commission has adopted new regulation which defines maximum permissible levels of load and no-load losses of transformers with rated power ≤ 3150 kVA, and minimum peak efficiency index for transformers with rated power > 3150 kVA up to 40 MVA. The impact of new regulation on the design and economy of transformer is presented.

Amorphous transformers, with up to 70 % lower no-load losses in comparison to the conventional transformers, could be an alternative with respect to energy efficiency. Although their initial price is higher than the price of conventional transformers, some studies show that they might have economic advantages.

The increasing penetration of distributed energy sources can cause an increase in voltage variations in low voltage networks. To keep the voltage within limits defined by EN50160, voltage regulated distribution transformers could be used.

Although mineral oil has been used as a dielectric fluid in transformers for many years, there are some environmentally friendlier alternatives – natural and synthetic ester-based fluids.

Key words: energy efficiency, ecodesign, distribution transformer, ester fluids

1. INTRODUCTION

Nowadays, greenhouse gas emission in the atmosphere, considering its influence on global warming and climate change, is the biggest environmental challenge. There are many heat-trapping gases (from methane to water vapor), but carbon dioxide puts us at the greatest risk of irreversible changes if it continues to accumulate unabated in the atmosphere. In order to reduce carbon dioxide levels in the atmosphere, the energy produced from fossil fuels needs to be reduced. To do this both energy efficiency and usage of renewable energy sources (wind, solar …) need to be increased.

At the EU level, the ecodesign of products is regulated by the Ecodesign Directive (2009/125/EC) [1]. Ecodesign requirements are aimed at improving energy efficiency by integrating environmental issues and life-cycle thinking already in the product design phase. Following those requirements, European

Commission has adopted new regulations setting new (lower) permissible maximum levels of load and no-load losses for transformers [2].

In the next paragraph the influence of new levels of losses on the design, price, weight and dimensions of modern distribution transformers is discussed, as well as the economic characteristics of amorphous transformers. Furthermore, voltage regulated distribution transformers for networks with renewables are analyzed. Finally, ecological insulations liquids are considered.

2. ENERGY EFFICIENCY

2.1. Ecodesign requirements

Having regard to Ecodesign Directive 2009/125/EC [1] and to the environmental and economic aspect of transformers, European Commission has adopted new regulations for medium power transformers. New ecodesign requirements [2] define maximum permissible levels of load and no-load losses of transformers with rated power ≤ 3150 kVA, and minimum peak efficiency index for transformers with rated power > 3150 kVA up to 40 MVA. This paper focuses on the distribution transformers. Comparing to current standard EN50464-1 [3] which defines levels Ak, Bk, Ck, Dk for load losses and Ao, Bo, Co, Do and Eo for no-load losses, new levels (Table I) are considerably lower, especially for no-load losses. No-load losses are far more reduced in comparison to reduction of load losses because of the fact that their share in total losses of distribution transformers is more than 70 % [4]. For three-phase liquid immersed distribution transformers new permissible levels from 1 July 2015 are CkAo for rated power ≤ 1000 kVA and BkAo for rated power > 1000 kVA. From 1 July 2021 levels come to an even lower level Ak(Ao-10%). New ecodesign requirements for liquid immersed distribution transformers are given in Table I.

Table I – Maximum load (P_k) and no-load losses (P_o) for three-phase liquid immersed distribution transformers with Um ≤ 24 kV

	Tier 1 (from 1 July 2015)				Tier 2 (from 1 July 2021)			
Rated Power (kVA)	Maximum load losses P_k (W)		Maximum no-load losses P_o (W)		Maximum load losses P_k (W)		Maximum no-load losses P_o (W)	
≤ 25		900		70		600		63
50		1100		90		750		81
100		1750		145		1250		130
160		2350		210		1750		189
250		3250		300		2350		270
315	Ck	3900	Ao	360		2800		324
400		4600		430		3250		387
500		5500		510	Ak	3900	Ao-10%	459
630		6500		600		4600		540
800		8400		650		6000		585
1000		10500		770		7600		693
1250		11000		950		9500		855
1600		14000		1200		12000		1080
2000	Bk	18000	Ao	1450		15000		1305
2500		22000		1750		18500		1575
3150		27500		2200		23000		1980

2.2. Impact of ecodesign on a conventional transformer design and economic evaluation

In this paragraph the influence of new ecodesign requirements (lower losses) on the price of material, weight, dimensions and design of the distribution transformer is researched.

2.2.1. Influence on the price and weight of the transformer

On Figure 1 the influence of losses on the price and weight of three-phase distribution transformers (20/0.42 kV, Dyn5) for 4 different rated power; 250, 400, 630 and 1000 kVA is shown.

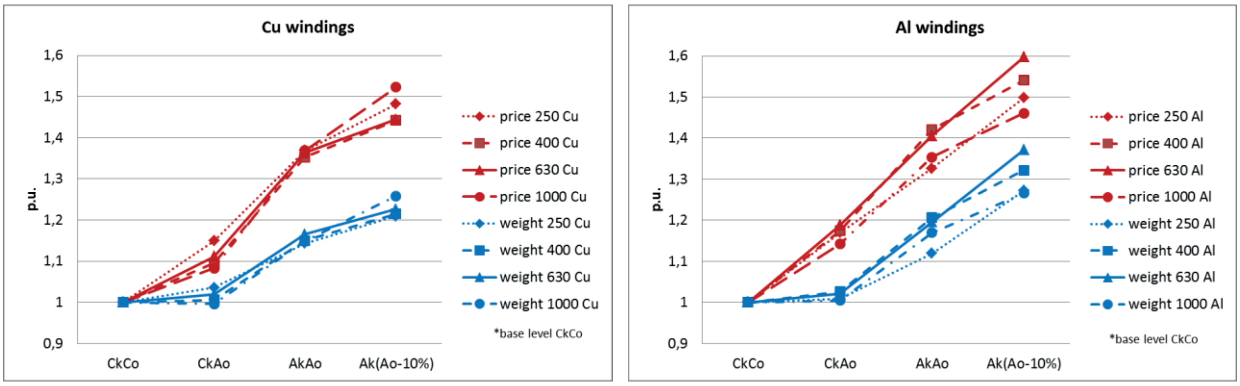

Figure 1 – Influence of the losses on the price of material and weight of the distribution transformers

As shown on Figure 1, ecodesign requirements increase the price of the transformer.

For the particular case, the average price increases for the transformers with copper (Cu) windings are 11% (CkCo->CkAo), 23% (CkAo->AkAo) and 8% (AkAo->Ak(Ao-10%)).

For the transformers with aluminium (Al) windings the price increases are somewhat higher. Average increases are 17% (CkCo->CkAo), 18% (CkAo->AkAo) and 11% (AkAo->Ak(Ao-10%)).

Regarding the weight of transformer, it approximately remains the same for both levels CkCo and CkAo. Lower levels of losses increase the weight. Transition from level CkAo to level AkAo increase the weight in average 14% (Cu) and 16% (Al). Finally, transition from AkAo to Ak(Ao-10%) increase the weight in average 7 % for the transformers with Cu windings and 12 % for the transformers with Al windings.

2.2.2. Influence on the dimensions of transformer

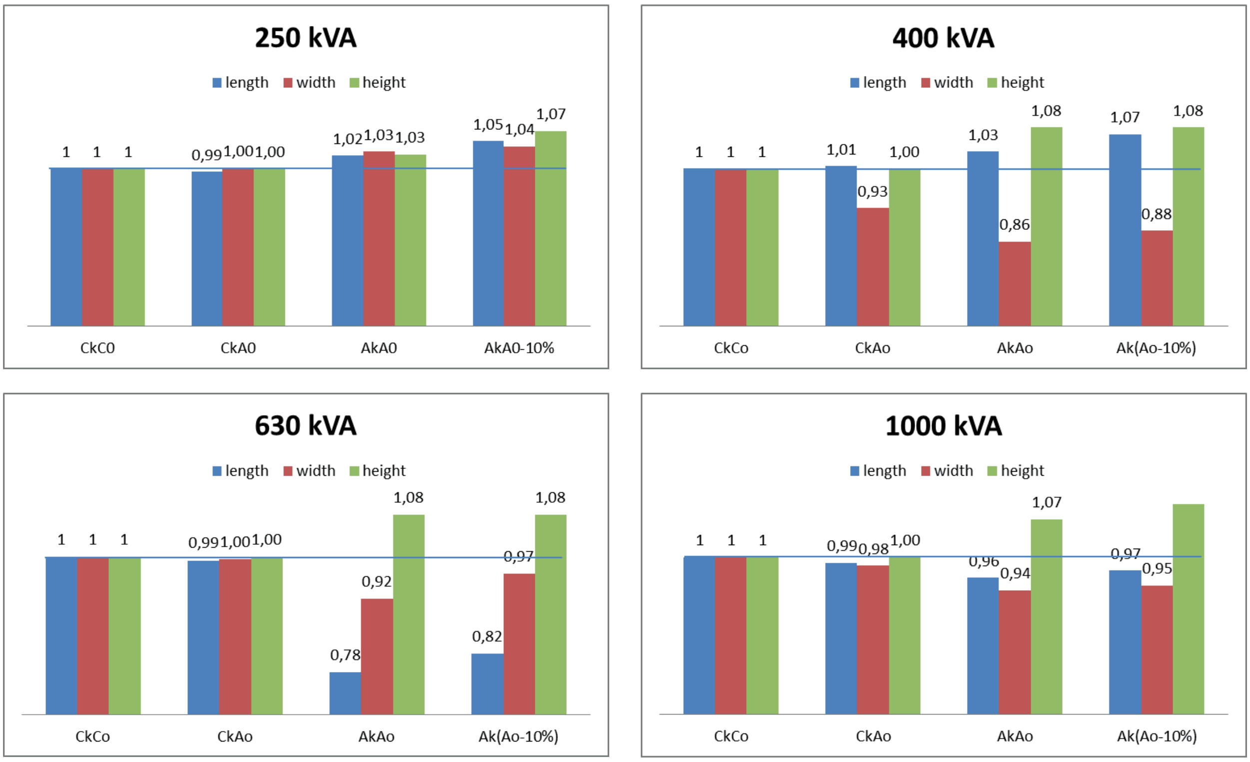

Figure 2 – Influence of the losses on the dimensions of distribution transformers (Al)

Figure 2 shows that new ecodesign requirements do not change significantly the dimensions of transformer. Similarly to weights, dimensions for levels CkCo and CkAo are almost the same. For lower level of losses, height of transformer increases but not more than 10%. Layout dimensions of transformer depend on the optimization of cooling system. Although the active parts is growing as the losses decrease, layout dimension of transformer mainly remain just a bit higher (up to 7%) or decrease. The reason for that is because lower levels of losses require less cooling system and therefore the increasing of active part doesn't reflect to the increasing of layout dimensions of the transformer. Analysis is valid for transformers with both Cu and Al windings.

2.2.3. Influence on the design of the transformer

As it can be seen from Figures 1 and 2, weight and dimensions of the transformer remain almost the same if the level CkCo is replaced with ecodesign required level CkAo. That means that the new transformer can replace the old one in the same space. In the transformer it was achieved by replacing classical grain oriented material (M5) in the core with low loss domain refined material (HGO-DR23).Further reduction of losses (to levels AkAo and Ak(Ao-10%)) requires higher cross section area of conductors and larger active part. It's interesting that, although heavier, transformers mainly keep their layout dimensions because of smaller cooling system.

2.3. Amorphous metal transformers (AMT)

The fact that AMT have up to 70 % lower no-load losses than the conventional distribution transformers makes them suitable related to ecodesign requirements. As stated before, reduction in transformer losses not only saves the current availability of electricity but also helps to reduce future generation needs. This, in turn, will help to reduce CO_2 and other gas emissions, providing a further benefit to the environment. However, amorphous transformers still have higher initial price, dimensions and noise level. Amorphous metal transformers have been used for more then 25 years, but on European market their share is negligible. Due to global movement of environmental protection, energy saving and continuous improvement of amorphous metal characteristics, their importance and share on the EU market may potentially begin to grow.

The amorphous metal used for amorphous transformers is alloy of iron, silicon and boron. To achieve an amorphous structure in a solid metal, the molten metal must be solidified very rapidly so that crystallization cannot take place. Amorphous metal is formed into ribbons, about 25 microns thick and with 3 sizes available width: 142, 170 and 213 mm, which are used to form rectangular shaped wound core. There are 2 three phase core designs types available: 3 phase 5 limbs transformer core and 3 phase 3 limbs transformer core.

2.3.1. Economic evaluation of AMT

Due to the different loss levels and initial price, the optimal way to compare cost effectiveness of amorphous and conventional distribution transformer is the Total Owning Cost (TOC) method. TOC is equal to the sum of transformer purchasing price plus the cost of transformer losses throughout the transformer lifetime. TOC can be calculated using the formula [5]:

$$TOC = PP + A \cdot P_o + B \cdot P_k, \quad (1)$$

where PP – is the purchase price of transformer
A – represents the assigned cost of no-load losses per watt
P_o – is the rated no-load loss
B – is the assigned cost of load losses per watt
P_k – is the rated load loss.

P_o and P_k are transformer rated losses. Values A and B depend on the expected loading of the transformer and energy prices. The choice of the factors A and B is difficult since they depend on the expected loading of the transformer, which is often unknown, and energy prices, which are volatile, as well as interest rate and the anticipated economic lifetime. Typically, the value of A ranges from less than 1 to 14 EUR/Watt and B is between 0.2 and 5 EUR/Watt. Below a relatively simple method for determining the A and B factor for distribution transformers is proposed.

A and B factors are calculated as follows [5]:

$$A = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \quad (2)$$

$$B = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \cdot \left(\frac{I_l}{I_r}\right)^2 = A \cdot \left(\frac{I_l}{I_r}\right)^2 \quad (3)$$

where: i – interest rate [%/year]
n – lifetime [years]
C_{kWh} – kWh price [EUR/kWh]
8760 – number of hours in a year [h/year]
I_l – loading current [A]
I_r – rated current [A]

Three different studies will be presented: one from USA [6], the other one from China [7] (both analyzed in [8]) and the last one from France [9].

In first two studies following values were considered: i=5%, C_{kWh}=0.04 EUR/kWh and n=30 years. The load losses will have 10 % and 20 % in relation to no-load losses, which are typical values for countryside and town distributions.

USA study shows total evaluation of different types of 50 kVA liquid-filled single phase type transformers according to the Table II:

Table II – Total evaluation of different types of 50 kVA transformers in USA

Type of transformer	Amorphous core type and Cu winding	Core type M2 and Cu winding	Core type M6 and Al winding
Price	1,540 €	1,190 €	1,050 €
No-Load losses	40 W	130 W	200 W
Load losses	720 W	880 W	1,400 W
Evaluated no-load loss	216 €	702 €	1,080 €
Evaluated load losses 10% / 20%	390 € / 780 €	470 € / 940 €	760 € / 1,520 €
Total evaluation	2,146 € / 2,536 €	2,362 €/ 2,832 €	2,890 € / 3,650 €

Although the amorphous transfomer has the highest initial price, considering the values taken for interest rate, kWh price, lifetime and lossess, it also has the lowest total owning cost which in this particular case makes it the most economic choise, considering the low values of load and no-load losses.

In the second study load losses and no-load losses are compared for distribution transformers 100 kVA and 500 kVA, classified as SBH15 and S11 type transformers. SBH15 is an amorphous core type and S11 is a typical low loss traditional liquid filled distribution transformer. The evaluation in this particular case (Table III) also shows more expensive transformer (amorphous core type) to be more economic choice considering losses and price. If a higher loss valuation would be used, the advantages for amorphous core material would be even greater.

Table III – Total evaluation of different types of 100 kVA and 500 kVA transformers in Chin

Type of transformer	100 kVA AMDT (SBH15)	100 kVA Conventional (S11)	500 kVA AMDT (SBH15)	500 kVA Conventional (S11)
Price	3,450 €	2,980 €	9,360 €	7,980 €
No-Load losses	75 W	200 W	240 W	680 W
Load losses	1,500 W	1,500 W	5,150 €	5,150 W
Evaluated no-load loss	405 €	1,080 €	1,290 €	3670 €
Evaluated load losses 10% / 20%	810/1,620 €	810/1,620 €	2,780 € / 5,560 €	2,780 € / 5,560 €
Total evaluation	4,665 € / 5,475 €	4,870 € / 5,680 €	13,430 € / 16,210 €	14,430 € / 17,210 €

From these two studies, the amorphous core material has economic advantages and shows, under these circumstances, to be the preferable option, although a relatively conservative loss valuation is used.

The third study shows different results although the values for A, B, P_o and P_k are unknown in the article. According to the study by EDF [9] made on 400 kVA 3-phase transformers with the loss level CkAo/2 and CkBo, the initial price of the amorphous transformer is 44 % higher and profitability is visible after approximately 27 years (Figure 3).

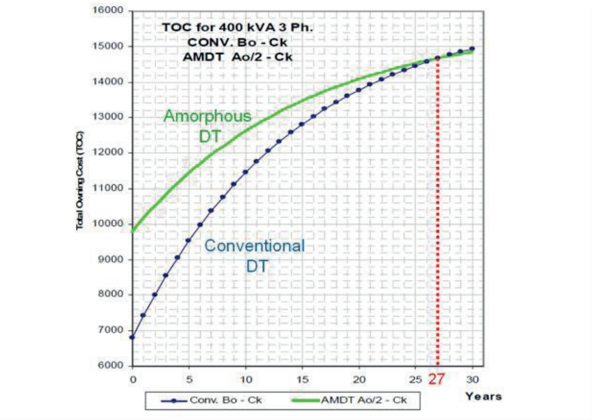

Figure 3 – Economic evaluation of AMT (EDF)

3. RENEWABLES

In the past electrical energy has predominantly been generated in large centralized power plants, but due to environment concerns and constant increase in fossil fuel price, the new trend in the modern power industry is towards renewable energy. Therefore, in 2008 the European Union has made "European plan on climate change" (also known as "European 20-20-20 targets") with three key objectives: a 20% reduction in EU greenhouse gas emissions from 1990 levels, raising the share of EU energy consumption produced from renewable resources to 20% and a 20% improvement in the EU's energy efficiency.

However, renewable energy plants have also some disadvantages: reliability of supply, large cost of initial investment, difficulty in obtaining the quantities of energy that are as large as those produced by traditional power plant and decentralized power generation. This last mentioned disadvantage has great influence on the standard design of the distribution transformer. Transformers in this distribution system have typically been designed to ensure a constant load flow from higher to lower voltage levels, but the large growth of distributed energy sources can lead to temporary reverse feeding from low voltage to medium or even high voltage.

3.1. Regulated distribution transformers (RDT)

Standard distribution transformer regulates the voltage usually in the range ±2x2,5% or ±1x4% of the rated voltage with off-load tap changer because it can only be switched when the transformer is de-energized.

The increasing penetration of distributed energy sources can cause an increase in voltage variations in low voltage networks. In order to keep voltage in the range U_n±10 %, as required by standard [10], it is necessary to increase the regulation range as well as to enable automatic voltage regulation especially in relation to smart grid. Transformers capable of fulfilling those requirements are called voltage regulated distribution transformers. Basically, there are two types of those transformers. In first, on-load voltage regulator is placed directly in the low voltage (secondary) circuit. With this solution the regulation range is limited to app. ±4% while only one turn is switched off or on. To expand the regulation range, additional off-load tap changer in the high voltage side of transformer is used. It can only be switched when the transformer is de-energized.

In the second type voltage regulator is a part of primary circuit of transformer (Figure 4) with voltage feedback from the secondary side. With this solution completely automatic on load regulation of secondary voltage in the range ±10 % is achieved with layout dimensions of transformers remaining the same.

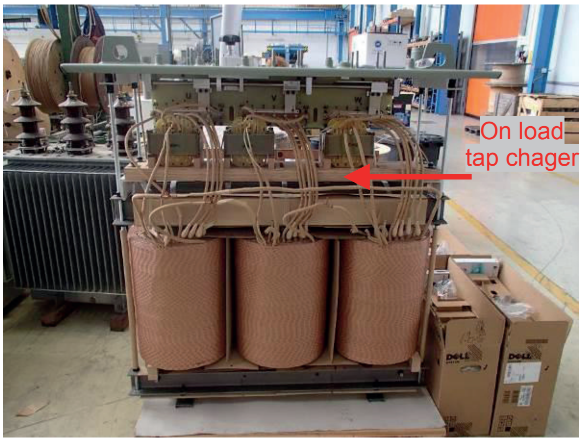

Figure 4 – Regulated distribution transformer (Končar D&ST)

Figure 5 – RDT after short circuit test

Voltage regulator is mounted at the same place as usual off load tap changer, but it requires more space in height. Such transformers must be designed with special attention in order to withstand short circuit forces. Figure 5 shows active part of RDT after successful short circuit withstand test.

Regulated distribution transformers are heavier and considerably more expensive than standard distribution transformers, mostly due to the size and price of the on-load voltage regulator.

4. ECOLOGICAL INSULATION LIQUIDS

Traditional mineral oils have been used as a dielectric fluid in generations of transformers although they have low biodegradation rate and low fire resistance. As the industry is migrating in the direction of environmental awareness, today in the market there are environmentally friendly alternatives. Natural and synthetic ester-based dielectric fluids have considerably higher both biodegradation rate and fire resistance. The flash point of such insulation liquids is 270-330 °C which is far more than 145 °C for mineral oils. Furthermore, both natural and synthetic esters are classified as being "readily biodegradable" which means that 90 % of biodegradation occurs within 28 days [11]. Figure 6 shows biodegradation rate of insulation fluids used in transformers.

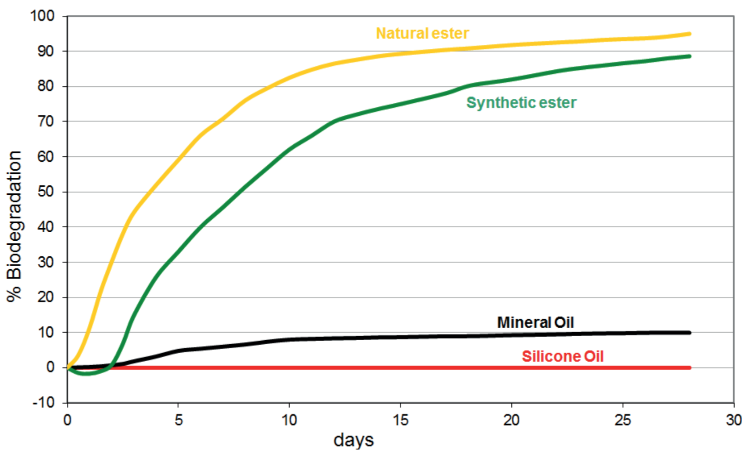

Figure 6 – Biodegradation rates of transformer insulation fluids

Ester insulation liquids have considerably higher moisture tolerance than mineral oils which means that they can absorb higher amount of water without compromising their dielectric properties. That has beneficial effect on the cellulose working life.

However, the ester immersed transformers compared to those filled with mineral oil must have larger cooling surface due to higher viscosity of esters. Furthermore, such liquids are more expensive than mineral oil (natural app. 3 times, synthetic app. 4 times). Because of that ester immersed transformers are currently approximately 25 % more expensive than conventional counterparts.

5. CONCLUSION

Industry is migrating in the direction of environmental awareness and improved energy efficiency. Distribution transformer with implemented newly adopted ecodesign requirements has basically the same design as standard transformer but with core generally made out of top quality domain refined material. Although the active parts is growing as the losses decrease, layout dimension of transformer mainly remain just a bit higher (up to 7%) or decrease.

Amorphous metal transformers with naturally up to 70% lower no-load losses than their traditional counterparts offer a noteworthy alternative. Because of higher initial price, dimensions and weight, they can be economically cost effective only if the capitalization is taken into account. Some analysis show that they are cost effective (USA, China), the other one that they are not (France).

Regulated distribution transformers with on-load tap changer in the primary side of transformer (instead of usual off-load tap changer) enable automatic voltage regulation in the secondary side in the range ± 10%. Thus the voltage can be kept within permissible range defined by EN50160 in spite of the stochastic voltage variations in the network with renewables. Such transformers keep the same layout dimensions as the standard ones.

Natural and synthetic ester-based insulation fluids are ecofriendly alternatives for minerals oils.

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