

# Simulated Thermal Fault: Assessing Dissolved Gas Analysis through Tube Heating Method on Mineral Oils and Natural Ester

Pär Wedin, Elena Minchak, Carl Wolmarans, Robert Fairholm, Jessica Singh, Kaveh Feyzabi, Thomas Norrby

**Summary** — Dissolved gas analysis (DGA) is the most widely used technique for monitoring transformer condition and detecting faults at an early stage. The quantity and type of gases that are produced by transformer faults and dissolved in the insulating liquid can reveal a lot about the nature and severity of the fault. To explore the variations in the dissolved gases based on the severity of the fault and the type of insulating liquid, we employed the Tube Heating Technique to simulate thermal faults at regulated temperatures up to 800 °C. To illustrate these differences, DGA data from commercially used insulating fluids such as inhibited and uninhibited mineral oils and a natural ester, will be presented.

**Keywords** — transformer, dissolved gas analysis, DGA, thermal fault, mineral oil, natural ester

## I. INTRODUCTION

The universally accepted technique for monitoring the condition of transformers to detect faults at an early stage is dissolved gas analysis (DGA) [1]. Faults in the transformer often generate gases that are dissolved in the insulating liquid. The quantity and type of gases provide significant information about the nature and severity of the fault.

Analysis of the gases in insulating oils using the gas chromatography method offers the highest accuracy and repeatability compared to hydrogen online monitoring and photoacoustic spectroscopy [2]. Oil samples need to be collected from operational transformers, and after undergoing several procedures, the extracted gases are analysed in the laboratory through gas chromatography. Compared to laboratory analysis, online DGA in power transformers is an even greater tool for predictive maintenance and ensuring the reliable operation of these critical assets [3]. By regularly analysing the dissolved gases in real-time or near real-time, abnormalities can be detected early, allowing for proactive maintenance and preventing potential catastrophic failures [4]. This technology enables timely intervention, helps in planning maintenance schedules, minimizes downtime, and ultimately extends the operational life of the transformer. Moreover, it assists in making informed de-

isions about whether specific transformers need immediate attention or can continue in operation, optimizing resource allocation and enhancing overall grid reliability.

To enhance research on interpreting dissolved gases, particularly for testing the next generation of insulating fluids, the establishment of a small-scale laboratory setup to replicate thermal faults (hotspots) is desirable. One such setup involving a heating wire has been proposed to emulate thermal faults under small-scale laboratory conditions, within a temperature range of up to 550°C [5]. Another publication suggested utilising resistance heating as the heat source; however, this method only reached temperatures of up to 320°C [6]. Notably, achieving a stable thermal fault simulation at temperatures exceeding 400°C on a small scale has proven to be challenging. Nevertheless, the tube heating method emerged as a promising alternative for replicating conditions resembling thermal faults at temperatures of up to 750°C [7, 8]. While this method appears to be reliable for simulating stable faults, it is imperative to verify the extent to which results obtained through this approach can accurately correlate with findings from operational transformers. This verification process is crucial for advancing diagnostic knowledge.

This study presents the development of a testing system designed to examine thermal faults using the tube heating method. An inhibited mineral oil, an uninhibited mineral oil, and a natural ester were exposed to thermal faults up to 800°C, and the resulting gases were analysed using dissolved gas analysis. The outcomes are subsequently presented and juxtaposed with the essential gas ratios employed in IEC 60599 [9] for forecasting fault types in transformers.

## II. MATERIALS AND METHODS

### A. INVESTIGATED LIQUIDS

Three different insulating liquids were subjected to testing using the experimental rig. These liquids include an inhibited mineral oil (inhibited MO, NYNAS NYTRO 10XN), an uninhibited mineral oil (uninhibited MO, NYNAS NYTRO Libra), and a natural ester (NYNAS NYTRO 100 NE). Table 1 provides an overview of the principal physical properties of the analysed insulating liquids. The boiling point distribution for the mineral oils is illustrated in Figure 1. Prior to testing, the insulating liquids were filtered and de-gassed using vacuum-filtration with 1.2 µm filters.

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TABLE I

OVERVIEW OF THE PHYSICAL PROPERTIES OF THE EXAMINED INSULATING LIQUIDS.

	Method	Uninhibited MO	Inhibited MO	Natural ester
Density at 20°C (kg/m <sup>3</sup> )	ASTM D4052	879.0	874.3	914.6
Viscosity at 40°C (mm <sup>2</sup> /s)	ASTM D445	9.295	7.638	40.59
Flash point, PM (°C)	ASTM D93A	153	142	275
Water content (ppm)	IEC 60814	4.4	3.1	41
Acidity (mg KOH/g)	IEC 62021-3	0.007	0.006	0.089
DDF at 90°C	IEC 60247	0.0004	0.0001	0.0096
IFT (mN/m)	ASTM D971	45.1	49.2	27.2
Color	ASTM D1500	<0.5	<0.5	<0.5
Inhibitor (%)	IEC 60666	n/a	0.28	n/a

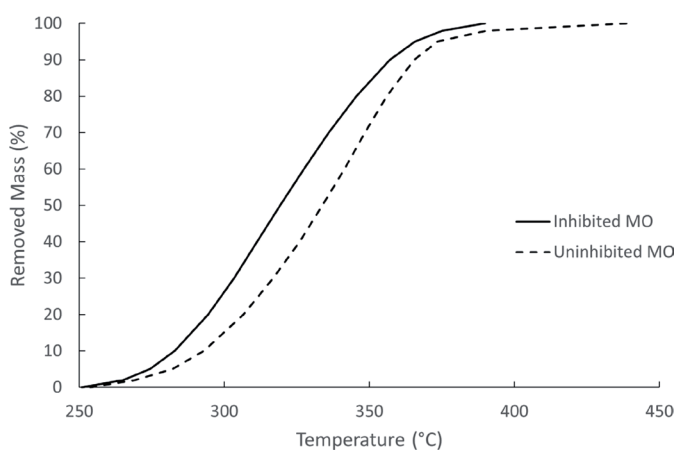


Fig. 1. Boiling Point Distributions for the two mineral oils according to ASTM D2887. Boiling point distribution data for the natural ester is unavailable.

DGA samples were collected via a dedicated sampling port in accordance with IEC 60475 [10]. Subsequently, the samples were sent to Bureau Veritas Commodities Antwerp NV, located in Antwerp, Belgium, for dissolved gas analysis following IEC 60567 [11].

## B. THE EXPERIMENTAL SETUP

The assembled setup is modelled after a configuration presented by Wang et al. at Manchester University [7], and is described elsewhere [12]. Broadly, it comprises a 12-litre stainless-steel oil tank connected by a pipe that passes through a furnace, and then returns to the tank, forming a closed loop (Figure 2).

The heating section incorporates a pipe furnace featuring a 15 cm heated zone, capable of achieving a maximum operating temperature of 1200°C. The pipe that passes through the furnace is enveloped in a copper mantle to enhance heat dispersion and transfer efficiency. A hole in the mantle facilitates insertion of a thermocouple for measuring the outer surface temperature of the steel pipe. Additionally, another thermocouple measures the interior temperature of the pipe at the same position.

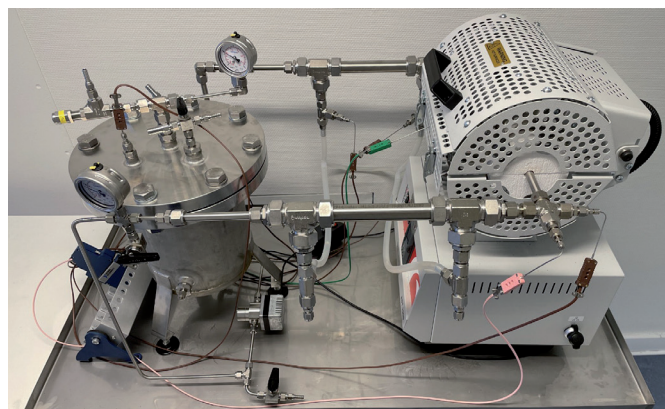


Fig. 2. Overview of the setup, including the tank, the pipe furnace, and the two water coolers before and after the furnace. The sampling port can be seen beneath the manometer attached to the pipe just before the inlet cooler of the furnace. An NI CompactDAQ chassis with a module for connecting eight thermocouples is visible in the lower left of the figure.

Throughout the experiment, temperature data is continuously collected from the thermocouples using a LabVIEW interface. Furthermore, temperature readings, target set points, and power levels from the furnace are continually logged. Pressures within the tank and the pipe are monitored through visual observation.

## C. EXPERIMENTAL PROCEDURE

The analysis of dissolved gases in the three insulating liquids was conducted at three hotspot temperatures: 275°C, 550°C, and 800°C. These temperatures align with the T<sub>1</sub>, T<sub>2</sub>, and T<sub>3</sub> thermal fault classifications as stipulated in IEC 60599. The duration of treatment was 168 hours, 6 hours, and 3 hours for the respective treatment temperatures of 275°C, 550°C, and 800°C.

When investigating a new liquid, it's necessary to replace the pipe that runs through the furnace with a fresh, unused pipe. The system is then pressurized to 1 bar above normal pressure for 24 hours to ensure proper sealing. Additionally, a level is employed to confirm that the pipe loop passing through the furnace maintains a horizontal orientation.

One 4L aluminium bottle is emptied into the clean tank, resulting in an 8L headspace within the tank. Upon activating the pump, the pressure is lowered to 0.2 bar. Subsequently, nitrogen gas is introduced to reach 1.0 bar. This pressure cycling is repeated for five cycles, achieving an oxygen content in the gas phase of less than 70 ppm. After this process, a blank DGA sample is collected from the sampling port while the pump operates at a low speed.

For the heat treatment, the pump is switched off, and the furnace's set point is adjusted to a suitable temperature,  $T_{SP}$ , that ensures the correct pipe temperature. Once the heat treatment concludes, the furnace is powered down and allowed to cool. To maintain consistency, the treatment duration is measured from when the furnace set point is set to  $T=T_{SP}$  until it is set to  $T=0^{\circ}\text{C}$ . As the furnace's external pipe temperature reaches around 350°C, the pump is turned on at a low flow rate to expedite cooling. When the external pipe temperature dips below 100°C, a DGA sample is obtained. By this stage, the tank's temperature has risen to 30-35°C.

### III. RESULTS AND DISCUSSION

The temperature profile during a six-hour heat treatment of the inhibited MO is displayed in Figure 3. From the moment the furnace initiates heating, it takes just under an hour for the outer pipe temperature to reach the intended hotspot temperature. The outer pipe temperature remains stable from that point until the heating is terminated. However, the measurements clearly show that the temperature inside the pipe is notably lower and displays significant fluctuations. Temperature fluctuations are also evident at the furnace outlet and, to a lesser extent, at the furnace inlet. The deactivated pump effectively prevents backflow, allowing liquid to flow only to and from the tank via the furnace outlet. This explains the differences in temperature fluctuations between the furnace inlet and outlet.

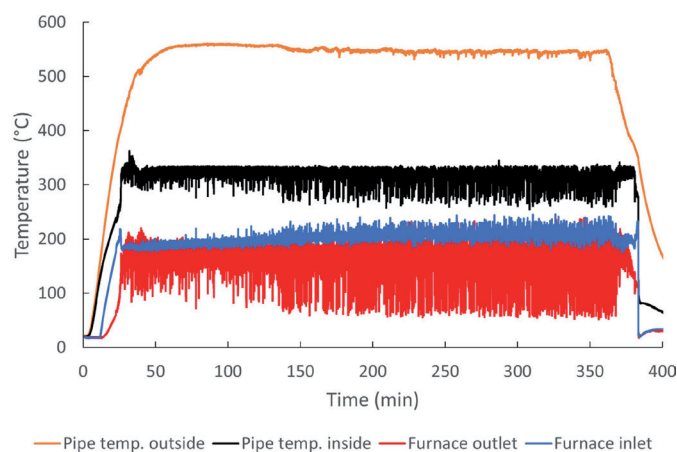


Fig. 3. Temperature profile of Inhibited MO run. Hotspot temperature corresponds to the outer pipe surface, and measurements are taken at the same location inside the pipe.

These temperature fluctuations stem from the evaporation of the MO within the furnace, causing hot gas to flow past the thermocouple at the outlet. As the hot gas reaches the cooler, it condenses, resulting in a pressure drop that compels cool oil to flow back past the thermocouple toward the furnace, as illustrated in Figure 4. This pressure drop is readily visible on the pipe's manometer and is often accompanied by an audible cracking sound emanating from the pipes. The temperature within the central section of the pipe, located inside the furnace, hovers around 325°C, corresponding to the midpoint of the boiling point distribution in Figure 1. Following the heat treatment, no discernible pressure buildup was observed within the tank. The temperature profile for the uninhibited MO exhibits analogous characteristics to that of the inhibited MO, differing primarily in the higher internal pipe temperature attributed to the elevated boiling point distribution.

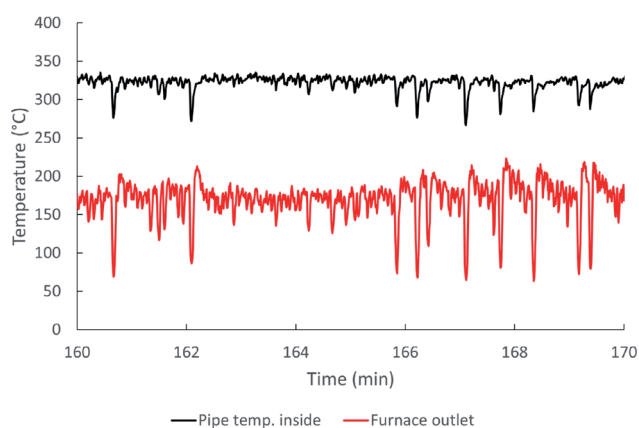


Fig. 4. Temperature fluctuations inside the pipe and at the furnace outlet for Inhibited MO.

The temperature profile for the natural ester significantly differs from that of the mineral oils, as depicted in Figure 5. Initially, the temperatures of the pipe's exterior, interior, and the furnace inlet and outlet steadily rise. However, around the 40-minute mark, the inner pipe temperature rapidly converges with the external temperature, and they remain virtually identical for the remainder of the heat treatment. Concurrently, the inlet and outlet temperatures decline

rapidly, approaching 44°C towards the conclusion of the heat treatment. During this period, the pressure within the tank also shows a notable increase of 0.2 bar, while maintaining an ambient temperature. With an 8L headspace, this pressure increment corresponds to a gas volume generated of 1.6L, significantly exceeding the volume within the pipes. This outcome likely signifies that, after approximately 40 minutes when the internal temperature reaches 340°C, the natural ester starts to decompose. The resulting gas evolution pushes the oil from the pipe into the tank.

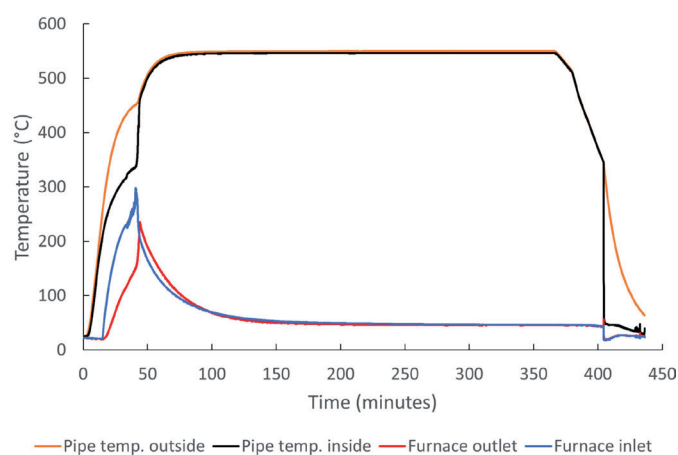


Fig. 5. Temperature profile during a typical run of the natural ester. The temperature profile suggests that the gas evolution during the thermal degradation of the oil has filled the pipe through the furnace with gas.

Some of the bulk properties of the oils were reanalysed following the 550°C heat treatment, and the results are presented in Table 2. The analysis of the key oil properties after the heat treatment reaffirmed the stability of mineral oil properties. Remarkably low DDF levels in the mineral oil samples indicate that even the uninhibited oil sample remained stable after the thermal treatment, preserving the oil's purity. Additionally, the low DDF levels provide confirmation that no contamination occurred during oil handling.

In contrast, the DDF level of the ester sample displayed a significant increase after exposure to the 550°C temperature, nearly four times higher than its initial value. This points to an elevated presence of polar contaminants, a consequence of fluid degradation. Furthermore, the deterioration of the ester oil is evident through a substantial increase in acidity attributed to the elevated quantity of fatty acids. The deterioration is further validated by a change in colour as per ASTM D1500.

TABLE II

KEY PHYSICAL PROPERTIES OF THE EXAMINED INSULATING LIQUIDS AFTER HEAT TREATMENT.

	Method	Uninhibited MO	Inhibited MO	Natural ester
Acidity (mg KOH/g)	IEC 62021-3	0.007	0.009	0.362
DDF at 90°C	IEC 60247	0.0002	0.0001	0.0399
IFT (mN/m)	ASTM D971	42.2	48.3	26.7
Color	ASTM D1500	<0.5	<0.5	0.8
Inhibitor (%)	IEC 60666	n/a	0.28	n/a

TABLE III

THE RESULTS FROM THE DISSOLVED GAS ANALYSIS FOR THE INSULATING LIQUIDS.  
THE TREATMENT DURATIONS AT DIFFERENT TEMPERATURES WERE 168 HOURS AT 275°C, 6 HOURS AT 550°C, AND 3 HOURS AT 800°C.  
THE DGA ANALYSIS OF THE BLANK SAMPLES SHOWS INSIGNIFICANT QUANTITIES OF THE GASES OF INTEREST.

	Uninhibited MO			Inhibited MO			Natural Ester		
	w275°C	550°C	800°C	275°C	550°C	800°C	275°C	550°C	800°C
Hydrogen	<5	268	5788	<5	183	2374	<5	189	1973
Methane	1.4	1529	18961	2.7	1100	19175	2.2	1409	5481
Ethane	3.3	1722	15452	2.4	1432	16402	<1	7132	11349
Ethylene	2.3	1691	28333	1.2	1533	32774	1.5	11519	29285
Acetylene	<1	<1	54	<1	<1	65	<1	12	91
Carbon monoxide	<25	<25	<25	<25	<25	<25	95	1316	1741
Carbon dioxide	<25	68	96	39	108	73	434	5519	8956
Nitrogen	72238	25157	41045	75419	31226	40051	68769	26542	42471
Oxygen	2652	7399	8155	4428	8777	6923	29150	3869	2128
Total dissolved gasses	74914	37846	117892	79886	44379	117854	98451	57512	103473
Total combustible gasses	9.9	5222	68597	11.1	4269	70808	98.7	21584	49918

As presented in Table 3, the uninhibited MO exhibits higher concentrations of detectable key gases when compared to its inhibited counterpart at 550°C. However, the natural ester sample contains notably larger quantities of ethane, ethylene, carbon monoxide, and carbon dioxide. The increased presence of carbon monoxide and carbon dioxide can likely be attributed to the molecular structure of esters, signifying pyrolysis or molecular decomposition due to the elevated temperature. The amount of gas produced is at 800°C is significantly greater, but the trend is less clear. The uninhibited MO produces more hydrogen but less ethylene than its inhibited counterpart. The ester produces less methane and ethane than the mineral oils but still significantly more carbon monoxide and carbon dioxide.

IEC 60599 [9] recommends specific key gas ratios for determining the probable type of fault in a transformer through dissolved gas analysis, as detailed in Table 4. The calculated key gas ratios for the examined oils are presented in Table

5. In the case of a T1 thermal fault, the acetylene-to-ethylene ratio and the methane-to-hydrogen ratio is non-significant, regardless of their values. However, the ethylene-to-ethane ratio should remain below one. While this criterion remains applicable for both mineral oils, it is surpassed by the natural ester. Nevertheless, it's worth noting that the calculated key gas ratios offer limited relevance due to the extremely low concentrations of dissolved gases in all three insulating liquids.

TABLE IV

THE DGA INTERPRETATION TABLE FOR THERMAL FAULTS FROM IEC 60599 [9].

Case	Characteristic fault	$C_2H_2/C_2H_4$	$CH_4/H_2$	$C_2H_4/C_2H_6$
T1	Thermal fault $t < 300^\circ C$	NS <sup>1</sup>	> 1 but NS <sup>1</sup>	< 1
T2	Thermal fault $300^\circ C < t < 700^\circ C$	< 0.1	> 1	1 to 4
T3	Thermal fault $t > 700^\circ C$	< 0.2	> 1	> 4

<sup>1</sup> NS = Non-significant whatever the value.

TABLE V

KEY GAS RATIOS FROM DGA OF INSULATING LIQUIDS AT THREE DIFFERENT TREATMENT TEMPERATURES, ACCORDING TO IEC 60599.

	$C_2H_2/C_2H_4$			$CH_4/H_2$			$C_2H_4/C_2H_6$		
	275°C	550°C	800°C	275°C	550°C	800°C	275°C	550°C	800°C
Uninhibited MO	0.4	0.0	0.0	0.3	5.7	3.3	0.7	1.0	1.8
Inhibited MO	0.8	0.0	0.0	0.5	6.0	8.1	0.5	1.1	2.0
Natural Ester	0.7	0.0	0.0	0.4	7.5	2.8	1.5	1.6	2.6

At a hotspot temperature of 550°C, all three liquids exhibit negligible acetylene content. The methane-to-hydrogen ratio exceeds one, while the ethylene-to-ethane ratio falls within the range of 1.0 to 1.6. As per the guidelines outlined in IEC 60599, presented in Table 4, it is suggested that the three liquids have undergone a T2 fault condition. This observation aligns well with the pipe temperature of 550°C.

At an 800°C hotspot temperature, all three insulating liquids demonstrate a significant increase in gas generation. By the conclusion of the heat treatment, there was a noticeable rise in tank pressure—approximately 0.3 bar for the mineral oils and 0.7 bar for the natural ester. Consequently, the DGA samples exhibited a substantial presence of dissolved gases, as illustrated in Table 3. Post-heat treatment, a notable amount of carbonized oil residue remained within the pipe for all three liquids. This aligns with the description of a T3 fault in accordance with IEC 60599.

While acetylene content remains insignificant and the methane-to-hydrogen ratio exceeds one, the ethylene-to-ethane ratio falls below the expected value for a T3 thermal fault. As shown in Table 4, a T3 thermal fault should exhibit an ethylene-to-ethane ratio greater than four. However, the experimental results range from 1.8 to

2.6. Xing et al. [8] investigated simulated thermal faults on natural esters using a similar tube heating method, and also reported lower than expected key gas ratios. One plausible explanation for this discrepancy could be the composition of the pipe passing through the furnace, which is constructed from stainless steel, as opposed to the copper typically found in transformers. Another possible contributing factor to the discrepancy could be the relatively large head space in the tank. The lower solubility of ethylene compared to ethene in the liquid phase could also result in an artificially low ethylene-to-ethane ratio [3, 13].

#### IV. CONCLUSIONS

This study introduces a setup built upon the Tube Heating Method, designed to replicate thermal faults at very high temperatures. Samples can be conveniently obtained through a standard sampling port and sent for analysis. Moreover, due to the setup's use of readily accessible components, it can be easily adapted for integration with online DGA equipment.

The gas generation resulting from the investigating of an inhibited mineral oil, an uninhibited mineral oil, and a natural ester was carried out using the tube heating method, reaching temperatures of up to 800°C to simulate a hotspot. Both mineral oils produced similar quantities of gas. In contrast, the natural ester generated significantly higher amounts of carbon monoxide and carbon dioxide compared to the mineral oils.

When assessing the ratios of key gases, as recommended by IEC 60599, at 275°C, the generated gas levels were too low to reliably determine the likely fault type. At 550°C, all three liquids exhibited ratios indicative of a T2 thermal fault. However, at 800°C, the ethylene-to-ethane ratio was lower than expected for a T3 thermal fault. This difference could potentially be attributed to the use of stainless steel for the pipe material, as opposed to the copper commonly used in transformers, or to the comparatively large headspace.

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