The benefits of inhibited transformer oils using the latest gas-to-liquids based technology

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ABSTRACT

Modern transformers are increasingly demanding more stringent performance requirements from transformer oils, to ensure higher system reliability and efficiency. Historically such oils have mainly been based on conventional paraffinic or naphthenic oils, which can have limitations. This paper provides an update on the features and benefits of inhibited transformer oils made using the latest gas-to-liquids (GTL) based technology.

INTRODUCTION

Paper content:

GTL based inhibited transformer oil
- What is it, how is it made?
- Transformer oil properties & performance benefits
  - Resistance to ageing & degradation in service
  - Cooling – thermal properties, fluidity
  - Electrical properties – lightning impulse breakdown
  - Ease of use – miscibility/compatibility with other oils
- Conclusions - benefits of GTL based transformer oils over conventional products

1. Gas-to-liquid (GTL) based inhibited transformer oil – what is it, how is it made?

Gas-to-liquid (GTL) based transformer oil is based upon a manufactured hydrocarbon (primarily iso-paraffinic) derived initially from gas. Natural gas (methane) is converted in a three-stage process, into a range of gas-to-liquid products including base oils suitable for making transformer oils, using proprietary technology. First, the methane is reacted with oxygen to create synthesis gas. Then the synthesis gas is converted into liquid waxy hydrocarbons in a Fischer-Tropsch process. Finally, the liquid waxy hydrocarbons are upgraded (hydrocracked) using specially developed technology involving novel catalysts, and then distilled into a wide range of products, including transport fuels, base oils and feedstocks for the chemical industry. Figure 1 gives an overview of the GTL process.

Figure 1 GTL process

The world’s largest gas-to-liquids (GTL) plant, Pearl GTL is located in Ras Laffan Industrial City in the State of Qatar, and is a joint development by Qatar Petroleum and Shell. Its gas comes from the nearby North Field, the world’s largest single non-associated gas field. The plant started in 2011, and marks the successful culmination of
more than 30 years of development. Once manufactured the GTL base oils are shipped from Pearl to one of three
global storage hubs, situated in Hamburg, Houston and Hong Kong. From here they are sent to lubricant oil blending
plants (LOBP’s) to be made into finished products such as transformer oils.

2. GTL based transformer oil properties & performance benefits versus conventional hydrocarbon
products, using examples from the latest generation of Shell Diala products

The primary insulating oil performance requirements of insulation, cooling and preventing corrosion, depend on a
number of factors including: the base oil used to make the fluid, how it’s been processed, and also the type and level
of additivation. Crude oils used to make conventional hydrocarbon insulating oils can contain a wide variety of
aromatic, naphthenic and paraffinic hydrocarbons, and also sulphur, nitrogen or other hetero-cyclic species, these
influence the performance of the finished oil such as its ageing characteristics.

2.1 Resistance to ageing and degradation

Typically unsaturated and aromatic hydrocarbons and hetero-cyclic species if left in the oil, can be prone to more
rapid oxidative degradation, resulting ultimately in the formation of oil insoluble oxidation products (giving deposits
such as sludges), and oil soluble organic acids and polymeric species (giving thickened, potentially corrosive oil),
which will both shorten the life of the oil, the solid insulation, and the service interval of the transformer, and which
can give rise to costly and time consuming unplanned maintenance. All insulating oils will degrade in service with
time, but the rate at which this occurs can be controlled, by the lubricant developer’s knowledge of base oil and
additive chemistry.

Sulphur compounds found in crude and finished insulating oils, depending on their type and quantity (total sulphur
in crudes can be up to 2 % by weight or more), can function as natural antioxidants and/or sources of potentially
 corrosive sulphur [1]. Refining of the crude by distillation, hydrotreatment and/or solvent extraction can convert or
remove the most unstable components [2].

Amongst the most critical parameters for predicting the field performance of insulating oils are oxidative stability
using IEC 61125C, and the test for potentially corrosive sulphur (IEC 62535). Knowledge of the type and level of
sulphur species can be informative as to whether an oil could become potentially corrosive, although given the
complex range of different sulphur compounds present and how they may interact in a transformer, a detailed
chemical understanding and explanation is still far from clear and is the subject of active study [3].

Table 1 lists the typical IEC 61125C oxidative stability testing results from a conventional inhibited naphthenic
(Diala S3 ZX-I), and a GTL based inhibited hydrocarbon insulating oil (Diala S4 ZX-I). This test provides an insight
into the ability of the oils to resist degradation in transformers in service. GTL based transformer oils consist of
manufactured – uniform composition, high purity, primarily iso-paraffinic molecules with a narrow molecular
distribution. As can be seen such oils respond positively and well, and in a synergistic fashion to the addition of
synthetic antioxidant, readily exceeding the highest levels of oxidative stability as defined in section 7.1 of IEC
60296: Ed 4 2012, and capable of exceeding the performance of conventional inhibited oils.

| Table 1 |
2.2 Cooling – thermal properties, fluidity

IEC 61125C Oxidation Testing of a Conventional Inhibited Naphthenic and the new GTL Based, Insulating Oil

<table>
<thead>
<tr>
<th>Oxidation Stability</th>
<th>Limits IEC 60296</th>
<th>IEC 60296 – sect 7.1 Higher oxid stab &amp; low sulphur</th>
<th>Inhibited Diala S3 ZX-I</th>
<th>Inhibited Diala S4 ZX-I (GTL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 61125 C</td>
<td>164/500 hours</td>
<td>500 hours</td>
<td>max 1.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Total acidity, mgKOH/g</td>
<td>max 0.8</td>
<td>max 0.5</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sludge, % weight</td>
<td>max 0.8</td>
<td>max 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric dissipation factor (DDF) at 90 ºC</td>
<td>max 0.5</td>
<td>Max 0.5</td>
<td>0.009</td>
<td>0.001</td>
</tr>
</tbody>
</table>

In terms of minimising the potential risk of corrosive sulphur issues developing in an insulating oil in service, typically the lower the total sulphur content in the oil the better. As given the extremely long service life and variable operating conditions oils will meet in service, it is difficult to predict with certainty what chemical species could ultimately be formed given the broad range of sulphur species that can be present in commercial products. Such a trend favours the more highly refined inhibited products which have the lowest sulphur contents, often less than 40 ppm. The new GTL based transformer oil provides the possibility of achieving oils with no detectable sulphur (as per ISO 14596/ASTM D2622).

Inhibited oils are typically more refined than uninhibited oils, and therefore have the lowest levels of unstable molecules remaining. While uninhibited oils by their very nature contain a wider range and variety of less stable components, which are more susceptible to degradation, and therefore cannot provide such high levels of oxidative stability. See Figure 2 below which shows the induction time from IEC 61125C oxidation testing, for an uninhibited conventional naphthenic oil (Diala S2 ZU-I) versus the inhibited GTL product. The induction time is reached when the volatile acidity significantly exceeds 0.1 mg KOH/g indicating marked oxidation has occurred. The graph shows the greater resistance to degradation of the inhibited GTL, and then a characteristic, gradual and predictable, rate of oxidation, which can be readily monitored using conventional oil condition monitoring techniques as described in IEC 60422 “Mineral insulating oils in electrical equipment – supervision and maintenance”.

![Figure 2](image)

IEC 61125C induction period oxidation test, volatile acidity in mg KOH/g versus test time in days

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GTL transformer oils typically have a significantly higher flashpoint and lower density than other conventional hydrocarbon inhibited oils, supporting safer and simpler transformer operation and potentially design. The thermal properties of oil, such as its specific heat capacity and thermal conductivity, are proportional to its density. Figure 3 indicates the calculated values for inhibited GTL versus a high performance inhibited conventional product (Diala S3 ZX-I) and a market representative inhibited iso-paraffinic competitor product. As can be seen, both the specific heat capacity and the thermal capacity values are higher for the GTL based product, indicating enhanced thermal properties. This may result in cooling benefits for transformers in operation, allowing either higher loading or reducing the requirement for forced cooling, or some other design optimisation of the transformer such as a reduction in size.

Figure 3
Calculated thermal properties (approximate, specific heat capacity, and thermal conductivity of inhibited GTL transformer oil versus other inhibited oils)

In addition to the thermal properties, another important parameter which influences the ability of an oil to provide cooling in a transformer, is its fluidity or viscosity across the usual operating temperature range of the transformer. Usual temperature ranges are defined in various specifications, see for examples IEC 60076 part 1, which defines the normal ambient lower temperature limit for power transformers as -25°C. Figure 3 shows graphs of fluidity (viscosity) versus temperature for inhibited GTL transformer oil (Diala S4 ZX-I) versus other conventional oils, uninhibited (Diala S2 ZU-I ngt) and inhibited (Diala S3 ZX-I). At higher temperatures most of the oils have a good low, and comparable viscosity, facilitating good cooling. At lower temperatures most oils will thicken significantly which reduces their flow and cooling ability. As can be seen from the graph, the inhibited GTL thickens significantly less at lower temperatures than the conventional oils tested, meaning it will maintain its good fluidity and flow properties better, even under these extreme conditions.
2.3 Electrical properties – lightning impulse breakdown

Transformer oils in service can be subjected to switching or lightning transient voltage stress. The influence of such surges on the oil can cause complex impulse breakdown events to occur. The resistance of insulating oils to such events in service can be evaluated in the laboratory. Two oils Diala S4 ZX-I (inhibited GTL) and Diala S3 ZX-I (conventional inhibited oil) both with a water content < 10 ppm, were tested for their lightning impulse breakdown in both needle-sphere and needle-plane geometry’s. Testing was at the University of Manchester, in the School of Electrical and Electronic Engineering. Needle-plane & needle-sphere electrode configurations were used (gap typically 25 mm, using positive & negative impulses) set up as below in figure 5. An 8 stage impulse generator with a maximum voltage of 800 kV and 4 kJ energy, was used to deliver the standard lightning impulse of 1.2/50 microseconds.

Figure 4
Fluidity (viscosity, cSt) versus temperature (°C) for inhibited GTL transformer oil (Diala S4 ZX-I) versus other conventional oils, uninhibited (Diala S2 ZU-I ngt) and inhibited (Diala S3 ZX-I)

Figure 5
Needle-plane & needle-sphere electrode configurations for lightning impulse breakdown testing
Figure 6
Average lightning impulse breakdown voltage (kV) of inhibited GTL oil (Diala S4 ZX-I) versus conventional inhibited oil (Diala S3 ZX-I), 25 mm electrode gap unless specified

The graph in figure 6 shows that the inhibited GTL oil has a significantly higher lightning impulse breakdown voltage than the inhibited conventional oil it was tested against, using both needle-sphere and needle-plane electrode geometry's, and with both positive and negative polarities. This indicates that Diala S4 ZX-I has a greater ability to withstand severe voltage transients in service such as those due to switching or lightning strikes, compared to the other tested oil.

2.4 Ease of use – miscibility/compatibility with other oils

To evaluate and clarify the effect of mixing GTL based transformer oils in service with other hydrocarbon transformer oils, especially in terms of miscibility/compatibility and resulting performance, a variety of tests were undertaken with uninhibited and inhibited conventional transformer oils (paraffinic and naphthenic), both aged and unaged, and in different ratios and combinations, this has previously been reported[4]. Testing was primarily using the IEC 61125C oxidation test, and a test derived from IEC 62535, to simulate and assess expected ageing in service, and potential miscibility/compatibility issues. The testing found no miscibility, compatibility, or solvency issues, confirming that GTL based transformer oils are generally miscible and compatible with existing hydrocarbon transformer oils, and can be used alongside such traditional products. It also confirmed that when mixing transformer oils, the resultant product typically displays resultant performance properties that are an average of the type and quantity of its constituent parts. This is irrespective of whether the oils are inhibited or uninhibited, unused or used, or whether the oil types are naphthenic or paraffinic, or a mixture of the two.

Compatibility of insulating oils is dealt with by IEC 60422 “Mineral insulating oils in electrical equipment – supervision and maintenance”. Section 6.12 states that unused oils conforming to IEC 60296, and containing the same or no additives are considered to be compatible with each other and can be mixed in any proportion. It recommends oils of the same type are used for topping up/refilling. Also that problems are not normally found when <5% unused oil is added to used oil (not heavily aged), but that higher levels with heavily aged oils may lead to precipitation. If in doubt it is advisable to run a compatibility test or consult the oil supplier.
Figure 7
Oxidative stability for mixed uninhibited Diala S2 ZU-I (15%) with inhibited Diala S3 ZX-I or Diala S4 ZX-I (85%) by IEC 61125 C (500 hr test)

If an uninhibited oil is mixed with an inhibited oil, then the resultant mixed oil typically displays performance properties that are an average of the type and quantity of its constituent parts. Figure 7 illustrates what happens to the oxidative stability of an uninhibited oil (Diala S2 ZU-I at 15%) when mixed with an inhibited oil (conventional high performance Diala S3 ZX-I at 85%, and GTL based Diala S4 ZX-I at 85%). These ratios are to simulate an extreme case of around 15% residual oil remaining in a transformer on draining and refilling. The impact on the conventional inhibited oil (S3 ZX-I) is that it no longer meets the highest oxidative stability requirements of IEC 60296:2012 (section 7.1). The GTL based inhibited oil S4 ZX-I clearly has a much higher oxidative stability even after mixing with the same 15% uninhibited oil, and is still able to meet the highest oxidative stability requirements of IEC 60296:2012.

CONCLUSIONS

This paper has shown how GTL inhibited transformer oils with their exceptional resistance to degradation and superior antioxidant response, can meet and exceed the IEC 60296:Ed 4 2012 highest oxidative stability, and low sulphur specification. It’s essentially zero sulphur content minimises the possibility of oil related corrosive sulphur developing in the transformer. It has well defined and consistent composition and, therefore, consistent performance, and has high purity consisting of only base oil and antioxidant. Modelling predicts good to superior cooling in service. It has a strong ability to withstand severe voltage transients. The product is easy to use with other conventional oils, no significant compatibility/miscibility or solvency issues were observed in the laboratory evaluation of the various mixtures of transformer oils.

The above performance features can provide electricity transmission/distribution customers with increased transformer reliability and efficiency, beyond those available with traditional products. The new GTL based oil has been tested and evaluated in the laboratory and in transformers, and the list of transformer manufacturers and utility companies who endorse and use the product is growing rapidly.
REFERENCES


