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Heat Transfer Fluid Deposit in Retainer of Mechanical Seal

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Abstract: Mechanical seals in industrial pumps play a critical role in preventing heat-transfer fluid leakage, particularly under high-temperature operating conditions. A key component of this system is the seal head, which functions as a compression mechanism using a spring to maintain contact between the sealing surfaces. However, the performance of springs can deteriorate due to the accumulation of deposits resulting from prolonged exposure to elevated temperatures, operating pressure, and fluid degradation, ultimately leading to seal failure and fluid leakage. This study investigated the thermal stability of the reservoir fluid Therminol 66 (TM-66) and its impact on seal performance under long-term thermal exposure. The methodology included direct observation of failed seals, thermogravimetric analysis (TGA) at temperatures of 75, 150, 250, and 350 °C for durations of 3, 6, and 12 h, and chemical characterization using Fourier Transform Infrared Spectroscopy (FTIR). Additionally, the thermal degradation behavior was assessed through activation energy estimation based on the weight loss data obtained from TGA. FTIR results revealed that phenylcyclohexane was the dominant compound in TM-66, with a relative intensity of 0.803119. The thermogravimetric data demonstrated that higher temperatures and longer exposure times significantly accelerated the fluid evaporation and mass loss. Activation energy analysis confirmed that thermal degradation is more likely to occur under extended high-temperature conditions. These findings highlight the importance of maintaining a reservoir fluid temperature below 75°C to minimize deposit buildup in the seal chamber and ensure the long-term reliability and efficiency of the mechanical seal system.
Keywords: Seal Head; Mechanical Seal Face; Spring; Thermogravimetri; Retainer

1. Introduction

Mechanical seals are critical components designed to prevent fluid leakage from a pump stuffing box to the external environment. In the event of a mechanical seal failure, the pump must be shut down immediately, as leakage, especially of high-temperature or hazardous chemical fluids, poses significant environmental and safety risks. Consequently, mechanical seals must adhere to technical standards, such as API 682, which dictate the design and operational parameters of sealing systems [1,2]. Mechanical seal failures have been extensively studied due to their complex nature, involving tribological interactions [3], friction [4,5], wear [6], surface roughness [7,8], and lubrication film [9]. Moreover, the selection of seal materials, such as metal bellows, secondary components, contact surfaces, and springs, plays a vital role in system reliability. The properties of the heat transfer fluid, equipment and piping design, and prevailing failure modes also contribute to the mechanisms of seal degradation. Typically, seal failure is indicated by fluid leakage into the atmosphere in single-seal systems or leakage of the buffer or barrier fluid into the process or externally in dual-seal systems.

This study specifically focuses on the failure of dual mechanical seals, which can be configured with either a buffer fluid (at a lower pressure than the process fluid) or a barrier fluid (at a higher pressure). Warda et al. [10], conducted an experimental investigation on the performance of integral radial and axial pump designs under various operating conditions, including changes in rotational speed and barrier fluid inlet temperature. Their work was supported by CFD simulations using ANSYS

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FLUENT to analyze the flow characteristics. The results demonstrated that the standard *k-ε* turbulence model provided acceptable predictions, and that the radial outlet configuration exhibited lower performance than the tangential outlet owing to vortex formation at the radial outlet port.

Key factors contributing to leakage and seal failure include high rotational speeds and the progressive degradation of spring performance, which reduce stiffness and alter the system's natural frequency. While centrifugal forces can help reduce leakage rates, they also elevate frictional heat, necessitating a narrower seal face design to minimize both friction and leakage [11]. To ensure that the fluid temperature remains safely below its boiling point, referred to as the "fluid temperature limit"a specific thermal margin is required. As a general rule, the fluid temperature within the seal cavity should be maintained at least 15°C below the boiling point to preserve optimal viscosity [12].

1.1. *Heat Transfer Fluids*

In this study, the heat transfer fluid used was Therminol 66 (TM-66), which comprises a mixture of partially hydrogenated terphenyls (74–87%), terphenyls (3–8%), heavy polyphenyls, quaterphenyls, and other hydrogenation products (approximately 18%). To evaluate the thermal and chemical stability of TM-66, experimental tests were conducted to simulate fluid aging, including the observation of oxidation phenomena through changes in color and chemical characteristics. Previous studies have compared TM-66 with Therminol VP1 using thermogravimetric analysis (TGA), and the results indicated that VP1 exhibited higher heat transfer efficiency under the initial conditions. Nevertheless, the primary criteria for selecting heat transfer fluids remain low vapor pressure—to prevent overpressure in expansion tanks—and a low freezing point to avoid pipeline blockages [13]. Kawanaka et al. [14], employed molecular modeling to predict phase behavior and asphaltene precipitation in CO_2/oil mixtures using a statistical thermodynamics approach based on the Scott and Magat theory. The oxidative stability of heat transfer fluids is a critical indicator of the fluid lifespan, particularly in open systems. Thermal degradation can be identified by the presence of both low- and high-boiling-point fractions. Oxidation rates increase significantly at temperatures above 80°C and are exacerbated by turbulence within the expansion tank, which promotes a more homogeneous mixing of air and fluid. Mineral-based fluids are typically used for operations up to 282–302°C, while synthetic aromatic fluids can operate at temperatures up to 400°C [15].

1.2. *Operating Condition*

A heat transfer pump was used to circulate TM-66 at approximately 300°C to heat the product. Heat absorption is performed using either a double-pipe or shell-and-tube heat exchanger. The piping system was designed such that the flow from the main heater to the plant occurred via a header pipe, which then distributed the heat transfer fluid to various heating subsystems using smaller capacity centrifugal pumps. In this study, the pump used had a capacity of 60 m^3/h, a bearing bracket size of 45, a head of 16.5 m, a 6.8 kW motor, and an impeller with a diameter of 220 mm.

The pump was equipped with a tandem mechanical seal configuration in accordance with API Plan 682 and utilized an ANSI Plan 52 piping system. In this configuration, an external lubricant reservoir is circulated using an internal ring pump during normal operation. TM-66 was used as the buffer fluid in the sealing system. The fluid from the reservoir is typically recirculated into a vapor recovery system at a pressure lower than that in the primary seal chamber.

Numerous studies have explored methods to enhance the performance of mechanical-seals. Unlike previous studies, this study focuses specifically on the analysis of the seal head/retainer component within the tandem seal system based on API Plan 682 and Piping Plan 52, as applied to a TM-66 circulation pump. The primary emphasis is on the role of the heat transfer fluid, as mechanical seal failures frequently occur in various seal sizes and thermal circulation systems. Material characterization was conducted to identify the chemical composition and contaminants, and thermogravimetric testing of TM-66 was performed at various temperatures and exposure durations to comprehensively evaluate the thermal stability of the fluid.

2. Methodology

2.1 Mechanical seal observation

Leakage in the mechanical seal of a centrifugal pump within a thermal fluid circulation system was detected. In a tandem seal configuration, leakage commonly occurs at either the primary seal (lower position) or the tandem seal (upper position). If the primary seal fails, an increase in the reservoir fluid volume typically serves as an early indicator of failure. However, in this case, a leakage occurred at the tandem seal, causing the fluid to escape directly into the atmosphere, posing both safety risks and energy losses.

To maintain operational stability in the heat transfer system, a mechanical seal was employed in an Allweiler CNH-B type pump, which was specifically designed to handle the thermal fluid Therminol 66. Figure 1 illustrates the actual installation of the mechanical seal system, along with a schematic of its internal structure. The seal is designed to prevent the leakage of the heat transfer fluid and minimize the air ingress into the system, which could accelerate the thermal degradation of the fluid.

In the schematic, the red-shaded area indicates the flow path of the Therminol 66. Points A and B represent the inlet and outlet channels from the mechanical seal chamber to the reservoir, respectively, enabling the continuous circulation and cooling of the seal. Point C shows the flow of Therminol 66 from the pump impeller, and point D highlights a potential exposure point where air could enter the shaft area.

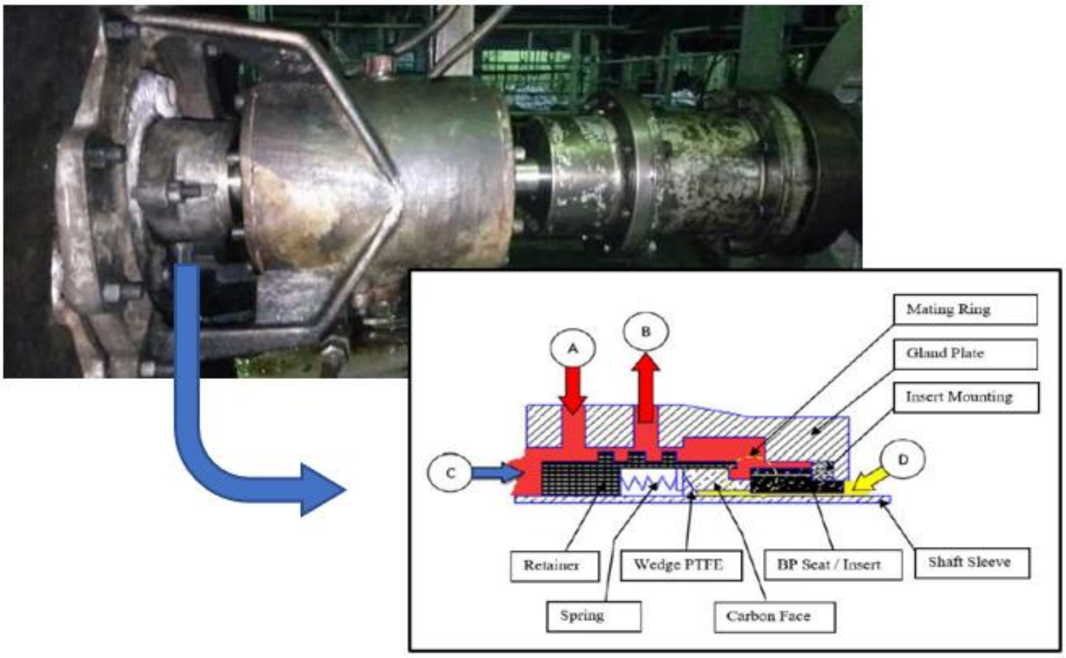


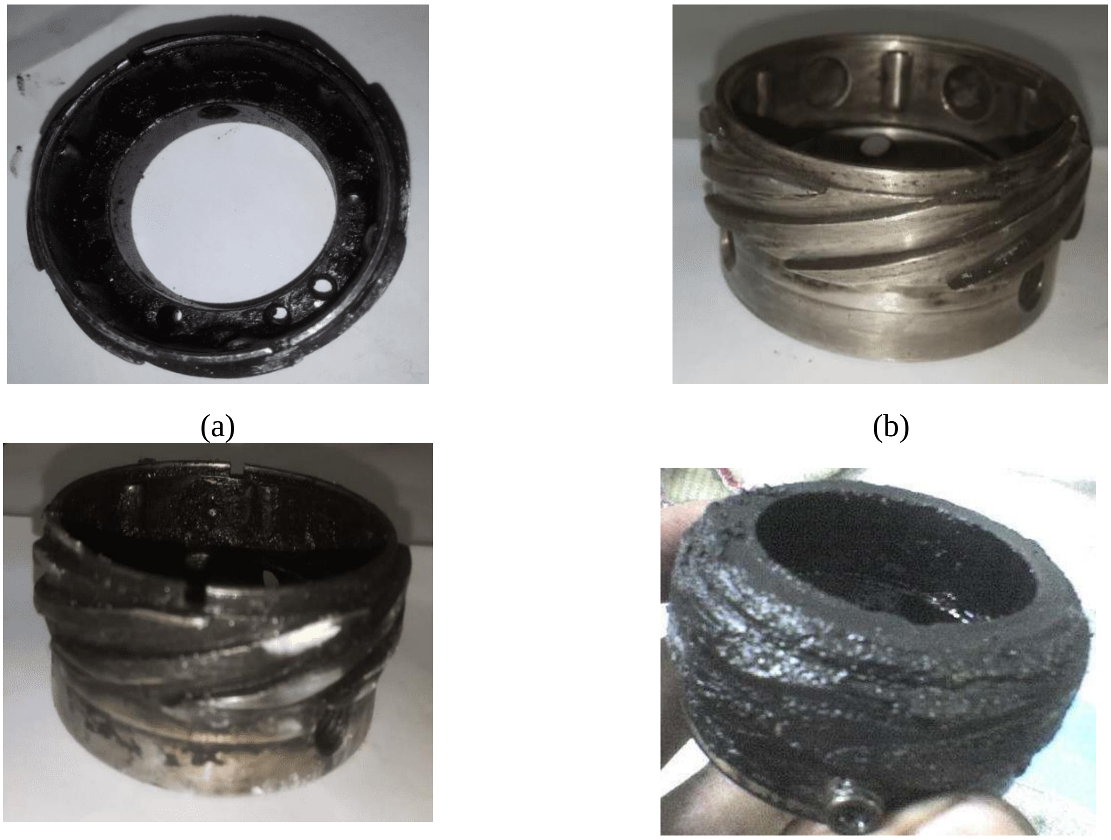
Figure 1. The internal configuration of the mechanical seal

The use of a mechanical seal with an integrated buffer system is crucial for preventing the oxidation of Therminol 66 and maintaining fluid purity, particularly under high-temperature operating conditions. The reliability of this system not only enhances the thermal efficiency but also extends the service life of the pump components. The mechanical seal position is shown in **Figure 1**, and indications of failure are shown in **Figure 2**, which displays fluid residue buildup on the seal head/retainer component.

The internal configuration of the mechanical seal consists of several key components: a retainer, PTFE wedge, spring, carbon face, back plate (BP) insert, and shaft sleeve. The carbon face, pressed by the spring, maintains a constant contact with the mating ring, compensating for the thermal expansion and wear during operation.

The circulation of the buffer fluid from point A to point B serves to cool the sealing surface while also preventing the ingress of external oxygen, which could accelerate the degradation of Therminol 66. Point D highlights the importance of maintaining minimal clearance in the shaft area to avoid excessive air infiltration from the surrounding atmosphere. This mechanical seal design significantly contributes to the reliability and longevity of thermal fluid pumps, particularly under prolonged high-temperature operating conditions.

This operational concept aligns with previous findings, which emphasize that an effective mechanical sealing and cooling system is essential for preventing thermal degradation and ensuring the chemical stability of heat transfer fluids in industrial processes [16–18].



(a) (b) (c) (d)

Figure 2. Seal head/retainer (a) internal view, (b) relatively clean condition, (c) dirty condition, and (d) very dirty condition and seal head failure on a mechanical seal

Figure 2a shows the internal condition of the seal head after disassembly from the failed pump. **Figure 2**b shows the same component after cleaning with a wire brush, and **Figure 2**c shows a condition with moderate contamination. **Figure 2**d illustrates a case of severe failure, with visible accumulation of heat-transfer or reservoir fluid deposits. Under these conditions, the mechanical seal compression mechanism fails to function properly because the spring cavity is filled with deposits (fouling). Additionally, the absence of a lubricating film on the sliding surfaces leads to sealing failure, resulting in unavoidable fluid leakage into the environment.

2.2 Fourier Transform Infrared Spectroscopy (FTIR)

To evaluate the potential chemical contamination of the heat transfer fluid Therminol 66 (TM-66), testing was conducted using Fourier-transform infrared (FTIR) spectroscopy. The primary objective of this analysis was to detect and identify functional groups and chemical compounds that may indicate chemical degradation or the presence of foreign contaminants in the system. The TM-66 fluid samples in **Figure 3** were collected from a pump that experienced mechanical seal failure and analyzed within a wavenumber range of 4000–400 cm^{-1}. The resulting FTIR spectra were used to determine the molecular structural changes potentially associated with oxidation or thermal processes occurring during operation.

Figure 3. Sample TM-66

2.3 Thermogravimetri test

Thermogravimetric Analysis (TGA) was conducted to assess the thermal stability of TM-66 against high-temperature exposure for different durations. The tests were conducted at temperatures of 75, 150, 250, and 350°C, with heating times of 3, 6, and 12 h. Each sample was placed on a precision scale inside the TGA furnace, and the mass change was recorded continuously as the sample was heated. The purpose of this test was to evaluate the rate of weight loss and observe the early indications of the thermal decomposition process. TGA data provide important information regarding the thermal resistance of the fluid and the potential for fouling or solid residue formation owing to degradation reactions.

2.4 Activation Energy Analysis

To strengthen the analysis of TM-66 thermal degradation, the activation energy (*Ea*) was estimated based on the weight loss data obtained from the TGA test. The activation energy represents the minimum amount of energy required for a thermal decomposition reaction to occur. The estimation was carried out using a mathematical approach based on the Arrhenius equation, which is expressed in Equations (1) and (2):

$$k = A\,exp\left(-\frac{E_a}{RT}\right) \tag{1}$$

$$ln\left(\frac{k_2}{k_1}\right) = \frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{2}$$

where *k* is the reaction rate, *A* is the frequency factor, *Ea* is the activation energy (kJ/mol), *and R* is the gas constant (8.314 J/mol). K) and *T* is the absolute temperature (*K*). By plotting the ln *k* value against 1/T1, a straight line was obtained, the gradient of which was used to calculate the *Ea* value. This analysis provides deep insights into the kinetic mechanism of TM-66 degradation under high-temperature operating conditions.

3. Results and Discussion

3.1 Spectrometry tests results

Fourier transform infrared spectroscopy (FTIR) analysis was performed on Therminol 66 (TM-66) heat transfer fluid samples to identify chemical structure changes that may occur owing to exposure to high temperatures during operation. This FTIR method allows the detection of specific functional groups through the absorption of certain wavelengths in the infrared spectrum, providing a comprehensive picture of the chemical compounds present in the fluid.

The FTIR test results are presented as an infrared spectrum graph in **Figure 4.** This graph shows the characteristic absorption patterns representing the main functional groups in the TM-66 compound. The detailed chemical composition of Therminol 66 identified in this test is summarized in **Table 1**. The data provide important information regarding the presence of aromatic compounds, carbonyl groups, and possible contaminants or degradation byproducts that can affect the thermal and chemical stability of the fluid during long-term operation.

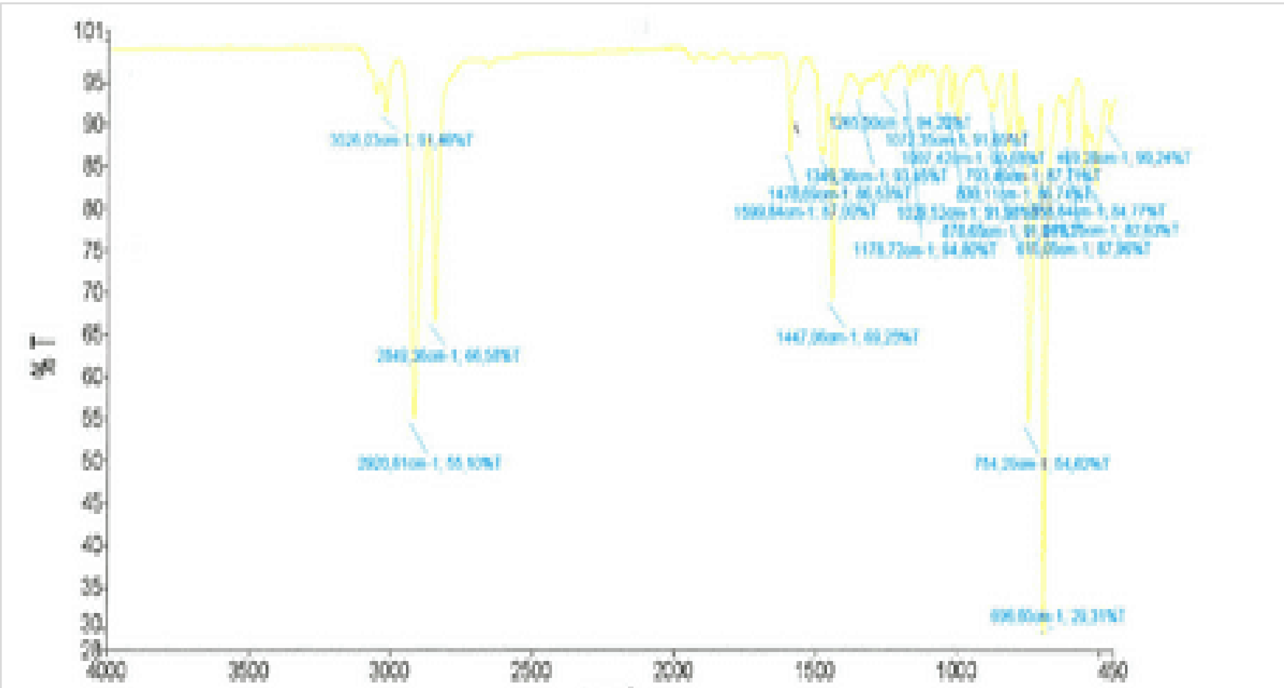


Figure 4. FTIR graph of TM-66 fluid test sample

These results can be used to further analyze the potential for oxidation reactions, residue formation, or changes in molecular structure, which are the main causes of decreased performance of the heat transfer system. The FTIR results were also used to evaluate the effectiveness of the mechanical sealing system in preventing contamination and maintaining the purity of the working fluid.

Table 1. TM-66 Spectrometry Test Results

Search Score	Search Reference Spectrum Descriptions
0.803119	Phenylcyclohexane
0.797044	Polystyrene
0.797044	Polystyrene
0.769475	Co Polymer Of 96% Styrene + 4% Divinyl
0.759045	Styrene/Butadine Copolymer 85% Styrene
0.759045	Styrene/Butadine Copolymer 85% Styrene
0.714173	Aminoethylpolystyrene-Hcl 0.1-0.3 Mmol
0.704128	Merryfield Polymer Fluka 0.7 mm Cl/G
0.702035	Aminoethylpolystyrene-Hcl 0.6 mmol
0.699147	4-Methylbenzyl Hydrylamine Polymer-Bound

Table 1. can be seen that the largest chemical composition of TM 66 is 0.803119 Phenylcyclohexane, this result is in accordance with what was also conveyed by Grirate et al [19], namely Hydroperoxide (C_6H_9OOH) will produce the opening of the cyclohexane ring. and also from the information on the safety data sheet of TM-66 used, namely that TM-66 contains 74-87% hydrogenated Therpenyl. for further research, Some data from these two references are used [13].

Tabel 2. Thermal properties of TM-66

Temperature °C	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Heat Capacity (kJ/kg.K)	Dinamics Viscosity (mPa.s)	Kinematics Viscosity (mm^2/s)	Vapour Pressure (absolute) (kPa)
75	971.9	0.115	1.751	6.995	7.19	0.015
150	920.6	0.110	2.014	1.520	1.65	0.400
250	847.9	0.100	2.379	0.570	0.67	9.250
350	765.9	0.088	2.766	0.320	0.42	85.740

Table 2 presents the thermal and physical properties of the Therminol 66 (TM-66) fluid at various temperatures from 75 to 350°C, including the density, thermal conductivity, specific heat capacity, dynamic viscosity, kinematic viscosity, and vapor pressure. At 75°C, TM-66 exhibited a high density of 971.9 kg/m³ and a thermal conductivity of 0.115 W/m. K, indicating good ability to store and transfer heat. The dynamic viscosity at this temperature is relatively high (6.995 mPa s), which supports the maintenance of a steady flow but implies a higher pumping energy requirement. As the temperature increased, the density decreased significantly from 971.9 kg/m³ at 75 °C to 765.9 kg/m³ at 350 °C. This reduction is typical for thermal fluids as molecular motion becomes stronger, leading to volume expansion [20]. The thermal conductivity exhibited a slight but continuous decrease from 0.115 W/m. K at 75°C to 0.088 W/m K at 350°C. This behavior is consistent with that of organic fluids, where phonon scattering at higher temperatures reduces the heat transfer efficiency. The specific heat capacity increased with temperature, starting from 1,751 kJ/kg. K to 2,766 kJ/kg.K. This trend suggests that the fluid requires more energy to raise its temperature as it becomes hotter, increasing its thermal energy storage capacity at high temperatures [17]. Dynamic viscosity decreases drastically with increasing temperature, from 6.995 mPa s at 75°C to only 0.320 mPa s at 350°C. Similarly, the kinematic viscosity also decreased, indicating that TM-66 becomes less resistant to flow as it is heated, which benefits the pumping performance at higher temperatures. The vapor pressure increased dramatically from 0.015 kPa at 75°C to 85.740 kPa at 350°C. This sharp increase is significant because high vapor pressure at high temperatures can cause cavitation and vapor shock in open systems, underscoring the need for a closed, pressurized circuit for high-temperature operation [16]. The data indicate that TM-66 is suitable for medium- to high-temperature heat-transfer applications because of its low viscosity at high temperatures and increased specific heat capacity.

However, the sharp increase in vapor pressure at temperatures above 250°C requires careful system design, particularly regarding system pressure and sealing.

3.2 Loss of weight analysis

The thermogravimetric test was conducted, and the average weight loss at a certain temperature and time was obtained, which was used as a reference in the operational process of the heat transfer fluid pump. The results of the tests are presented in **Tables 3** and **4**.

Table 3. Loss of weight of TM-66 Fluid (%)

T (°C)	3 h	6 h	12 h
75	0.00	0.08	0.16
150	0.60	0.98	45.49
250	75.26	9.96	55.06
350	98.94	99.28	99.26

Table 4. Loss Weight TM-66 (gram)

T(°C)	3h	6h	12h
75	0.0093	0.0081	0.0162
150	0.06	0.0981	4.5518
250	7.6622	1.0005	5.5205
350	9.921	9.9402	9.9479

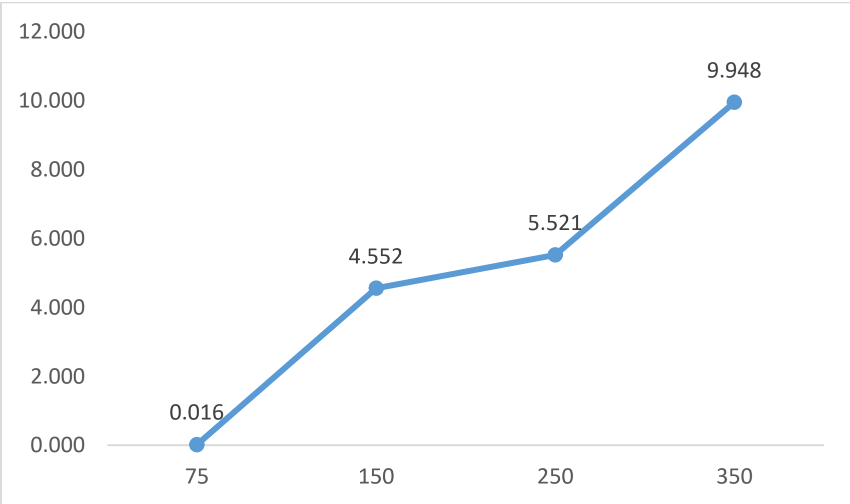


Figure 5. Test fluid weight loss graph

Based on the results presented in **Tables 3** and **4** and as illustrated in **Figure 5**, it is evident that the weight-loss trend in the TM-66 fluid increases with higher temperatures and longer exposure times. At the lowest test temperature of 75°C, the weight loss remained minimal, recorded at 0.00% after 3 h, 0.08% after 6 h, and 0.16% after 12 h. The corresponding mass loss was relatively small, as shown in **Table 4**, with a maximum of only 0.0162 g at 12 h. This indicates that TM-66 exhibits good thermal stability over a long period at lower temperatures. However, as the test temperature increased, fluid degradation became more pronounced. At 150°C, although the percentage weight loss after 3 and 6 h remained below 1%, a significant mass loss of 4.5518 g was observed after 12 h, indicating the onset of oxidative degradation processes. At 250°C, a significant increase in weight loss was recorded even at the initial stage, with a 75.26% decrease after 3 h, indicating substantial volatilization or thermal decomposition. At 350°C, TM-66 underwent almost complete degradation, with weight loss exceeding 98% in the first 3 h, maintaining this value for up to 12 h. This drastic weight loss confirms that TM-66 cannot maintain its structural integrity at temperatures approaching 350°C under the tested conditions.

The trend observed in **Figure 5** further illustrates that the rate of weight loss increased significantly beyond 250°C. The orange curve (lower temperature) shows a gradual increase in weight loss, whereas the blue curve (higher temperature) increases sharply, confirming that temperature plays a dominant role in the fluid degradation kinetics.

The thermal degradation of synthetic heat transfer fluids, such as TM-66, typically occurs via oxidative and thermal cracking mechanisms. Oxidation leads to the formation of weak organic acids, carbonaceous residues, and volatile products, especially when exposed to oxygen, as is possible in open-vent expansion tank systems [21]. In addition, decomposition at high temperatures can produce low molecular weight compounds that increase fluid volatility and increase mass loss [22]. Thus, it can be concluded that TM-66 fluid begins to show signs of oxidative degradation starting at approximately 150°C, with critical decomposition occurring above 250°C, and complete breakdown at 350°C in open-air conditions. For applications requiring long-term fluid stability, it is important to operate TM-66 below 250°C and in a closed-loop system to minimize oxygen exposure and subsequent degradation.

3.3 Confirmation of Energy Activation

Assuming a first-order degradation process and considering the temperature at which significant weight loss occurs (from 250 °C onwards), we can make a rough estimate. Using two points at 250 °C (523 K), approximately 75% weight loss after 3 h, and at 350°C (623 K), approximately 99% weight loss after 3 h. Following a simple two-point Arrhenius plot approach using Equation (2), the estimated activation energy for TM-66 degradation under the tested conditions was approximately 7.55 kJ/mol. This value is relatively low, indicating that TM-66 is susceptible to rapid degradation at high temperatures, particularly in oxygen-rich environments. This result is in line with previous studies reporting that synthetic organic heat transfer fluids tend to have activation energies ranging from 6 to 20 kJ/mol depending on the molecular structure and the presence of antioxidants [23].

4. Conclusion

Based on the results of experimental research on the heat transfer fluid Therminol 66 (TM-66), it can be concluded that the thermal and chemical stability of the fluid is greatly influenced by the operational temperature, particularly in the context of application in the mechanical seal system of centrifugal pumps. The thermogravimetric test data showed that the higher the exposure temperature, the greater the weight loss of the fluid sample. This weight loss indicates the evaporation, thermal degradation, and possible decomposition of the active compounds in TM-66. This condition is supported by the results of the FTIR test, which shows changes in intensity and shifts in the spectrum peaks at several wavelengths, indicating the modification of functional groups due to oxidation or thermolysis processes at high temperatures.

In the context of using a buffer fluid in a tandem mechanical seal system, the reservoir temperature plays a crucial role. Based on observations and experimental data, the temperature of the reservoir fluid should be maintained below 75°C to prevent excessive evaporation and the formation of deposits that can accumulate in the mechanical seal chamber. The deposits formed, as shown in the visual analysis and documentation of seal damage, have the potential to clog the spring chamber and interfere with seal compression, which ultimately causes sealing failure and fluid leakage into the atmosphere.

Furthermore, the activation energy analysis calculated from the weight-loss data also confirmed that the thermal degradation reaction of TM-66 requires lower energy at high temperatures, which means that the degradation process will occur faster if the temperature is not well controlled. Therefore, the design of the cooling system and temperature control in the reservoir should be seriously considered in long-term operations to maintain the integrity of the mechanical seal and extend the service life of the heat transfer fluid. Overall, this study emphasizes the importance of operational temperature control and the need for an effective sealing system to prevent fluid degradation and system damage, as well as to ensure the efficiency and reliability of industrial processes based on thermal fluids such as TM-66.

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