Triethylenglycol as Novel Heat Transfer Fluid for CPVT Collectors with Spectral Splitting

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Abstract

Concentrating PVT (CPVT) collectors using the approach of Spectral Splitting are designed to provide thermal energy at high temperature level and electricity simultaneously with optimised efficiency. Among others, the Spectral Splitting effect can be achieved by a combination of a solid and a liquid absorption filter. In such a case, the utilised liquid serves both as optical filter and as heat transfer fluid and needs to fulfil several optical and thermodynamic requirements. Triethylenglycol (TEG) was investigated as a potential candidate fluid for utilisation in a Spectral Splitting CPVT receiver with a desired output temperature of 200°C. The performed analysis involves the mathematical description of temperature-dependent fluid properties, thermal expansion measurement, long-term thermal stress, and UV exposure tests. The main parameters for monitoring possible impacts of the stress tests are the spectral and the weighted transmittance values of the fluid, as these are essential properties for a stable long-term operation of the considered CPVT collector including Spectral Splitting. The investigation of TEG confirmed its suitability for the described application. The characteristic of the spectral transmittance in initial state shows the required downwards step at a wavelength of 1100 nm that is essentially necessary for the combination with a solid filter in the Spectral Splitting configuration. The UV exposure with a dosage of 50 kWh/m² has negligible effect on the optical fluid properties. The long-term thermal stress tests caused an acceptable decrease in weighted transmittance of -3.2 percentage points within the spectral band from 780 nm to 1100 nm.

Keywords: Heat transfer fluid, Spectral Splitting, transmittance, temperature stress, UV exposure

1. Introduction

Solar energy reveals rapidly increasing relevance for tackling the central challenge of the century, the transition of the global energy supply towards emission-free solutions (REN21, 2020). Besides the established technologies of photovoltaics (PV) and solar thermal energy conversion (T), the combination of both as hybrid or PVT systems can have several advantages in terms of efficient area utilisation, reduction of installation costs or increase of electrical energy yield (Zenhäusern, 2017). If industrial energy demand with higher temperature requirements shall be supported by PVT, concentrating systems (CPVT) have to be considered. However, CPVT collectors have to deal with the challenge to prevent an overheating of the PV cells in order to ensure acceptable electrical energy conversion efficiency, while providing output temperatures as high as possible. The concept of “Spectral Splitting” appears to be a promising approach to overcome the described discrepancy (Imenes and Mills, 2004). Thereby, the full spectrum of the incident concentrated solar irradiance is split into several segments by selective reflection or absorption. The PV cells only receive the specific spectrum segment where the electrical energy conversion works with highest efficiency, whereas all other wavelength ranges of the spectrum are directly converted into heat within the thermal receiver part. In this way, the waste heat dissipation inside the PV cells and hence the cell temperature can be reduced, resulting in a significant increase of electrical conversion efficiency.

Various constructions of Spectral Splitting CPVT receivers have been developed over the last decades (Daneshazarian et al., 2018; George et al., 2019; Imenes and Mills, 2004; Mojiri et al., 2013). Heading towards experimentally viable solutions, compact receiver designs combining solid and liquid beam splitting appear to be highly suitable for implementation and possible subsequent product development, because their constructions are rather simple, and the solid absorption filter with selectable optical characteristics provides a certain adjustability of the ratio between electrical and thermal output (Huang et al., 2021). The fluid applied for such receiver constructions serves two different purposes. On the one hand, it works as the heat transfer fluid (HTF), extracting the heat absorbed by the solid filter and transferring it to the respective heat sink. On the other hand, the fluid is an important part of the Spectral Splitting concept, as it defines the upper threshold wavelength of the spectrum range provided to the PV

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cells. Pure water can be a potential fluid, but if operating temperatures beyond 100°C are targeted, pressurisation has to be applied in order to avoid phase changes. However, the considered receiver concepts are typically constructed with glass components, in some cases even using rectangular cross sections (Hangweirer et al., 2015), which are less resistant against high pressure. For this reason, other kinds of HTF apart from water with a boiling point above 100°C at nominal pressure are required for the considered utilisation in a Spectral Splitting receiver. Furthermore, the HTF is directly exposed to concentrated incident sunlight in this case, what might lead to degradation of the medium, depending on its specific type.

In order to examine the suitability of candidate fluids like Silicone oil, synthetic oils or glycols for the described Spectral Splitting application, Looser et al. (2014) performed a comprehensive investigation of 18 different liquids, also linked to previous work done by Everett et al. (2012). This study included initial optical transmittance measurements, long-term low temperature and high temperature exposure at 75°C resp. 150°C for a duration of 700 h, as well as UV light exposure for more than 500 h. Among all tested fluids, Propylene Glycol (PG) turned out to be best suitable in terms of spectral transmittance, temperature reliability and chemical stability at UV-exposure.

This significant research outcome of Looser et al. (2014) might have been the basis for subsequent experimental investigations and performance tests of Spectral Splitting receivers, e.g. published by Stanley et al. (2016), Mojiri et al. (2016) or Han et al. (2021), where PG was used as heat transfer fluid. However, the maximum output temperature experimentally reached so far with PG was reported with 120°C by Stanley et al. (2016). The long-term temperature test of Looser et al. (2014) was limited to 150°C, and the boiling point of PG under nominal pressure is specified with 187°C (Looser et al., 2014). If the output temperature of a CPVT collector using the described concept of Spectral Splitting shall be increased above 150°C, the durability of PG is not confirmed. Moreover, if the design output temperature is specified with 200°C, the utilisation of PG under nominal pressure is clearly not possible, as the boiling point would be exceeded.

Resch and Höller (2020) recently developed several new CPVT receiver designs including the Spectral Splitting approach of combining solid and liquid absorption filtering. Two main aims of this research work are the target output temperature of 200°C and the realisability as a prototype for performing experimental measurements. As the current state of knowledge described above did not provide an appropriate fluid that can fulfil the optical and physical requirements for the specified temperature limit and at nominal pressure, a screening of potential HTF with a boiling point above 200°C was conducted. Most promising as a novel candidate fluid for an application in the developed Spectral Splitting CPVT receiver design was found with Triethylenglycol (TEG) from the German supplier WITTIG Umweltchemie GmbH. The boiling point of TEG without pressurisation is between 280°C and 295°C, it has crystal clear appearance, it is non-toxic and readily soluble in water (WITTIG Umweltchemie GmbH, 2015a, 2015b). These similarities in chemical and physical properties of PG and TEG reinforced the assumption that TEG could provide suitability for Spectral Splitting applications comparable to PG but accompanied by a significantly higher boiling point. Nevertheless, to the best of the authors´ knowledge, the utilisation of TEG for the considered application is not reported yet. Therefore, the aim of this paper is to investigate the suitability of Triethylenglycol as heat transfer fluid and as the liquid filter part of the Spectral Splitting concept in combination with a solid absorption filter for an operating temperature up to 200°C.

2. Methodology

The performed analysis consists of a thorough characterisation of the TEG in its initial state and provides the most important thermodynamic properties in dependence of temperature, both graphically and mathematically. The investigation of the long-term stability of TEG involves a high-temperature test at 210°C for a duration of 700 h, a temperature cycling test within the range of 45°C to 210°C and for 180 cycles, as well as a UV exposure test for a duration of 833 h. Transmittance measurements were done in intervals of 100 h to observe potential changes in the optical properties of the fluid due to the applied stress tests.

2.1 Thermodynamic and physical properties of Triethylenglycol

Knowledge of fundamental thermodynamic and physical properties of a fluid is essential for its utilisation in a hydraulic system. If TEG shall be used as heat transfer fluid in the considered CPVT collector system with a nominal temperature span between 20°C and 200°C, the temperature dependency of the fluid characteristics is an important information. The supplier of TEG provided the following properties as a function of temperature in the range between -10°C and +160°C (WITTIG Umweltchemie GmbH, 2015c):

- Density ρ in kg/dm³
- Specific heat capacity c_p in kJ/kg·K
- Heat conductivity λ in W/m·K
- Dynamic viscosity η in mPa·s

The supplier´s property information is only given graphically, and the considered temperature range is limited to 160°C. If the TEG characteristics are required for modelling purposes, a mathematical description of the fluid properties and their temperature dependency is needed. For this reason, MATLAB was used to extract 12 to 14 data points per curve from the graphical description. Curve fitting functionalities of MATLAB were applied to those datasets for obtaining the temperature dependent specification of TEG as mathematical equations.

The density ρ and the specific heat capacity c_p are described by linear equations, whereas the dynamic viscosity η is approximated by an exponential function. The heat conductivity λ is constant over the considered temperature range. For modelling the heat transfer between a fluid and a solid surface, the Prandtl number Pr of the fluid is essentially required. Therefore, this additional parameter was calculated for TEG by using the following equation (von Böckh and Wetzel, 2009):

$$Pr = \frac{c_p \cdot \eta}{\lambda} \quad \text{(eq. 1)}$$

Subsequently, the temperature dependency of Pr is approximated by an exponential function.

2.2 Thermal expansion test

As the thermal expansion coefficient of TEG is not specified by the supplier, this parameter was gained experimentally. A graduated measuring glass with 100 ml content, made of borosilicate glass and standardised according to DIN EN ISO 4788, was filled with 50 ml TEG at 20°C. The measuring glass remained open to atmosphere and was heated up in steps of 20°C to a maximum temperature of 220°C, using a heating chamber MEMMERT UF160plus. The expanding volume could be directly observed at the scale of the measuring glass and is reported for each of the intermediate steady state temperatures. This experiment was carried out three times in the same way, and the results are averaged for each temperature. Therefore, reading errors can be minimised and a strong reliability of the experimental outcomes can be confirmed.

Mathematical description of the measurement datasets is done by approximating a quadratic polynomial, using the MATLAB curve fitting functionality.

2.3 Spectral transmittance measurement and weighted transmittance calculation

The fluid TEG is a significant part in combination with the solid absorption filter for realising the required Spectral Splitting effect. Therefore, the spectral transmittance τ_s of TEG at each specific wavelength of the entire solar spectrum is crucial. Transmittance measurement was done with the fluid in its initial state to confirm the suitability of TEG in terms of the optical filter requirements that are illustrated in Figure 1 for an ideal Spectral Splitting configuration. In this case, a perfect solid absorption filter (red dashed line) shows a step in its spectral transmittance from 0 % to 100 % at a wavelength of 780 nm, whereas an ideal fluid (blue dashed line) reveals a downwards step of τ_s from 100 % to 0 % at a wavelength of 1100 nm. This idealised arrangement of solid filter and fluid would provide a “spectral window” between 780 nm and 1100 nm, where the irradiance E is neither absorbed by the filter nor by the fluid but transmitted to the PV cells of the CPVT receiver. In all subsequent illustrations, this spectral window is summarised as “ideal filter”. The spectral irradiance E corresponds to the AM1.5 direct and circumsolar spectrum published by NREL (n.d.).

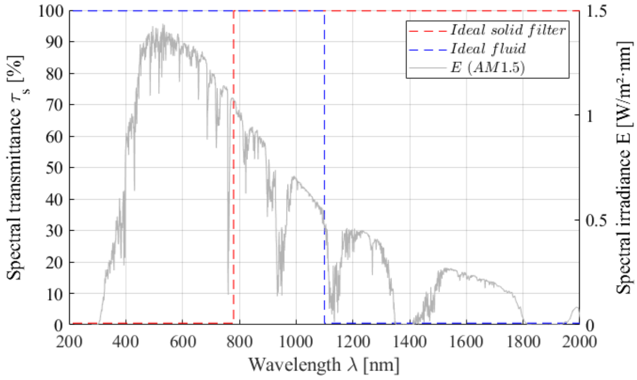

Fig. 1: Spectral transmittance τ_s of ideal solid filter and ideal fluid for application in a Spectral Splitting configuration

Besides the initial measurement, the spectral transmittance of the fluid was monitored periodically during the long-term stress tests described subsequently, for the purpose of detecting any change in the optical properties of TEG that could have an impact on the filtering effect. The spectrophotometer used for the transmittance measurements is a JASCO V-570 with a nominal wavelength spectrum from 250 nm to 2500 nm. A quartz glass cuvette, type 6030-UV, with a content of 3.5 ml and an optical length of 10 mm was filled with the corresponding TEG samples and inserted into the measuring beam of the spectrophotometer.

Additional to τ_s that specifies the transmittance for each single wavelength of the spectrum, an examination of the solar-weighted transmittance τ_w is meaningful for quantifying expected transmittance changes of the fluid by an exact number for a certain spectrum range. Furthermore, τ_w is related to the spectral irradiance and is therefore considering the varying intensity of the incident wavelengths. The calculation of τ_w is done for three ranges of the spectrum, corresponding to the three sections in Figure 1 that are given by the ideal filter: τ_{w1} from 280 nm to 780 nm, τ_{w2} from 781 nm to 1100 nm and τ_{w3} from 1101 nm to 2000 nm. The solar-weighted transmittance τ_w is calculated by the following equation (Miller et al., 2013):

$$\tau_w = \frac{\int \tau_s(\lambda) \cdot E(\lambda)\, d\lambda}{\int E(\lambda)\, d\lambda} \qquad \text{(eq. 2)}$$

2.4 Long-term exposure to UV light

In contrast to conventional solar thermal collectors, the HTF of the designed CPVT collector with Spectral Splitting is directly impinged with concentrated sunlight, because it flows through glass tubes instead of opaque pipes made of steel or copper. The high-energetic UV part of the solar spectrum can harm the surface of various materials, e.g. plastics, and it can also change the optical property of a fluid, as it was already shown during previous research work (Everett et al., 2012; Looser et al., 2014). For this reason, a long-term UV exposure test was applied to the investigated TEG as well. The specification for this test bases on the standard *IEC62108 – Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval* (IEC, 2007), demanding a total UV dosage of 50 kWh/m² ± 10 % for the spectrum range below 400 nm. A weathering test chamber ATLAS Ci4000 was used for this test. This chamber is equipped with xenon lamps that provide an irradiance of 60 W/m² in the broadband wavelength range between 300 nm and 400 nm. Hence, a test duration of 833 h was needed to reach the required accumulated UV dosage. Eight test tubes made of borosilicate glass with a content of 20 ml and an aluminum cap were filled with TEG in such a way that a small air bubble remained in the tube for compensating thermal expansion of the fluid, see Figure 2. The UV exposure test was started with all eight test tubes positioned in the weathering chamber. In intervals of 100 h respectively 133 h at the end of the procedure, one test tube was extracted from the chamber for measuring the transmittance of the fluid in the spectrophotometer.

Fig. 2: Test tube filled with TEG and remaining air bubble (foreground) and further test tubes prepared for long-term UV exposure test (background)

2.5 Long-term thermal stress by high-temperature exposure and temperature cycles

Besides the depicted stress of the HTF by exposure to UV light, the fluid must also withstand the claimed operating temperatures of the CPVT collector. Although the boiling point of TEG between 280°C and 295°C at nominal pressure promises principal suitability for operating the fluid at temperatures of 200°C and beyond, the impact of high temperature operation on the optical properties of TEG is unclear. Moreover, the investigations of Looser et al. (2014) on similar fluids like Propylene Glycol have already proven that high-temperature stress does influence the spectral transmittance and hence the filtering behaviour of such liquids. Therefore, conducting long-term thermal stress tests with TEG was essentially required to ascertain the applicability of the fluid for the described purpose. The investigation consisted of a high-temperature exposure for 700 h at a fluid temperature of 210°C ± 5°C and a temperature cycling test with varying fluid temperature between 45°C ± 5°C and 210°C ± 5°C for 180 cycles with a cycle time of 4 h each. The heating chamber MEMMERT UF160plus was used for both tests. The fluid samples were stored in Erlenmeyer flasks made of borosilicate glass with a content of 250 ml and sealed with silicone plugs, supported by a spring mechanism that prevents the plugs from being lifted due to rising pressure within the flasks, see Figure 3.

Fig. 3: Erlenmeyer flasks filled with TEG and sealed with silicone plugs including safety mechanism, before starting the high-temperature test. Sample "L" contains air, sample "N_2" is passivated with Nitrogen.

Two flasks for each test were filled with 200 ml of TEG. The remaining volume in the first flask was filled with air, while in the second one the air was replaced by Nitrogen. These two kinds of gas volume inside the flasks were chosen to analyse the influence of potential oxidation on the optical properties of TEG, if the fluid is in direct contact with closed air. Every 100 h, the flasks were opened to extract 20 ml of fluid for performing transmittance measurements. The Nitrogen passivation was re-established after each fluid extraction process.

3. Results

3.1 Temperature dependency of thermodynamic and physical properties of TEG

The following graphical and mathematical specification of the temperature dependency of major fluid parameters may be helpful for the utilisation of TEG as a heat transfer fluid in the temperature range up to 200°C. Figure 4 condenses the temperature characteristics of density ρ, specific heat capacity c_p, dynamic viscosity η and Prandtl number Pr as graphical illustrations. The square marks are values taken from the supplier´s data sheet, and the solid lines are fitted curves obtained by mathematical approximation. The Prandtl number Pr was not provided by the supplier but calculated from c_p, η and heat conductivity λ, see equation 1. Therefore, this curve does not contain any supporting points.

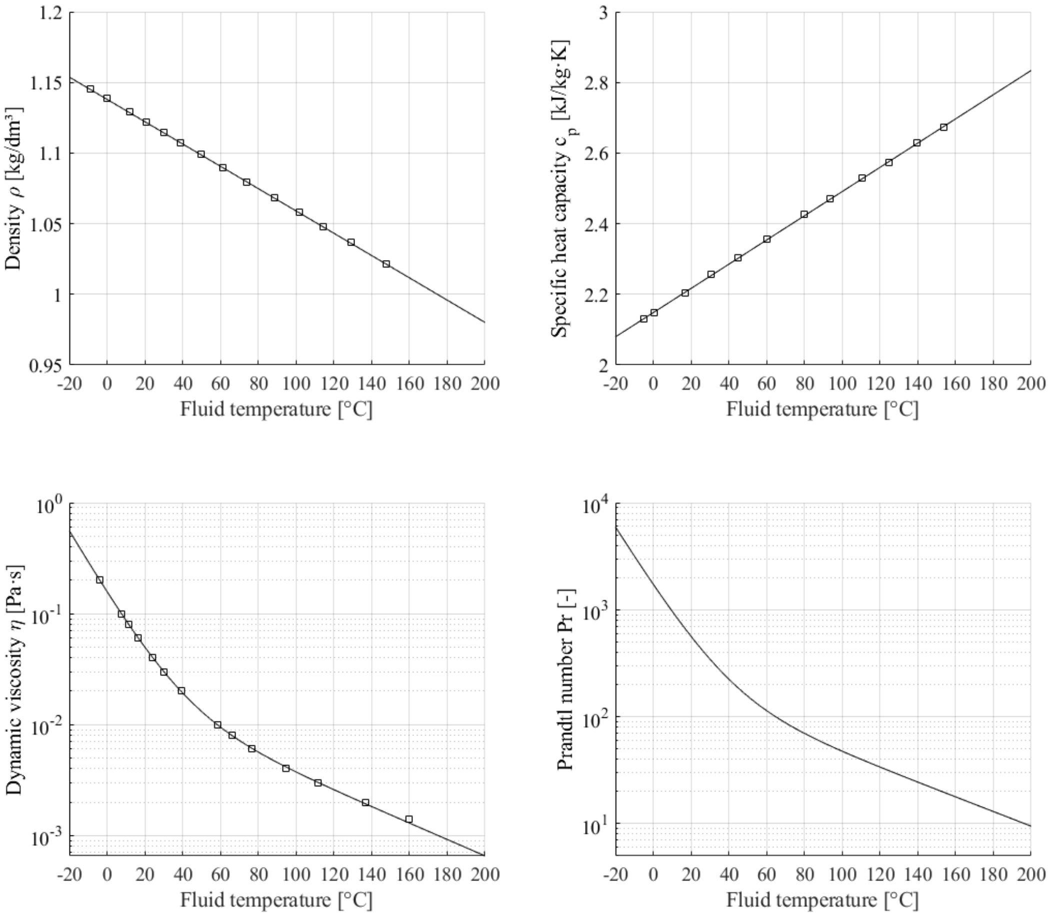

Fig. 4: Temperature dependency of major thermodynamic and physical properties of TEG: Density ρ in kg/dm³ (top left), specific heat capacity c_p in kJ/kg·K (top right), dynamic viscosity η in Pa·s (bottom left) and the Prandtl number Pr (bottom right)

The density ρ (in kg/dm³) of TEG is depicted in the top left quarter of Figure 4, showing a linear degression with rising fluid temperature. This characteristic is described by equation 3:

$$\rho(\vartheta) = 1.138 - 7.897 \cdot 10^{-4} \cdot \vartheta \quad \text{(eq. 3)}$$

By contrast, the specific heat capacity c_p (in kJ/kg·K) is increasing linearly with temperature, as illustrated in the top right quarter of Figure 4. Therefore, the mathematical approximation also reveals a linear equation as follows:

$$c_p(\vartheta) = 2.148 + 3.43 \cdot 10^{-3} \cdot \vartheta \quad \text{(eq. 4)}$$

A significant temperature dependency of the dynamic viscosity η (in Pa·s) can be obviously observed in the bottom left quarter of Figure 4, given in logarithmic scale on the y-axis. η of TEG falls from 49.923 mPa·s at a temperature of 20°C down to 0.655 mPa·s at 200°C, corresponding to a factor of 76.2. The mathematical approximation yields an exponential function to describe the temperature dependent characteristic of η:

$$\eta(\vartheta) = 0.1386 \cdot e^{-0.06739 \cdot \vartheta} + 0.01954 \cdot e^{-0.01698 \cdot \vartheta} \quad \text{(eq. 5)}$$

The Prandtl number Pr (dimensionless) is directly proportional to the dynamic viscosity η. Therefore, its temperature dependency illustrated in the bottom right quarter of Figure 4 is also approximated by an exponential function:

$$Pr(\vartheta) = 1519 \cdot e^{-0.06577 \cdot \vartheta} + 214.4 \cdot e^{-0.01553 \cdot \vartheta} \quad \text{(eq. 6)}$$

The heat conductivity λ of TEG is constant in the temperature range from -10°C to +160°C, as specified by the supplier (WITTIG Umweltchemie GmbH, 2015c):

$$\lambda(\vartheta) = const = 0.196 \frac{W}{m \cdot K} \quad \text{(eq. 7)}$$

Correct implementation of the described equations 3 to 6 implies the corresponding temperature ϑ to be given in °C. Moreover, the validity of the approximations for the temperature range between 160°C and 200°C is neither confirmed by the supplier of the fluid nor by any experimental verification yet.

3.2 Thermal expansion measurement and mathematical approximation

The graphical result of the thermal expansion experiment with TEG is presented in Figure 5. The measured increase of volume with rising temperature is normalised to the base temperature of 20°C. The square marks indicate the measurement results, averaged for each temperature step, whereas the solid line represents the illustrated mathematical approximation. For the temperature range considered within the described application of operating a CPVT receiver, the fluid expands by approx. 15 % when it is heated up from 20°C to 200°C.

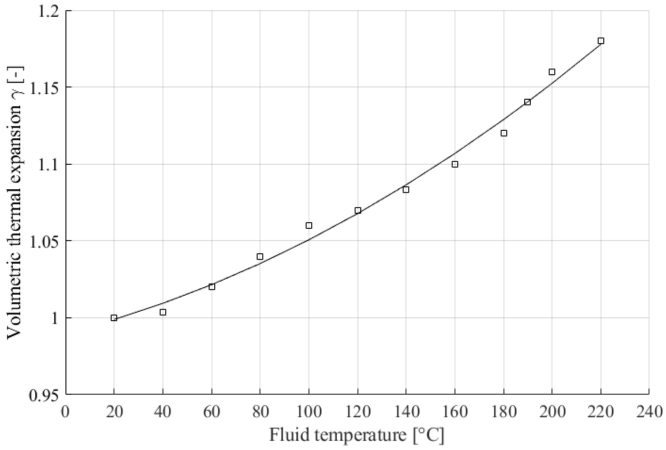

Fig. 5: Volumetric thermal expansion of TEG, normalised to base temperature 20°C

The mathematical description of the volumetric thermal expansion γ of TEG is provided by the quadratic polynomial in the following equation 8:

$$\gamma = \frac{V(\vartheta)}{V(20°C)} = 0.9901 + 3.989 \cdot 10^{-3} \cdot \vartheta + 2.065 \cdot 10^{-6} \cdot \vartheta^2 \quad \text{(eq. 8)}$$

The fluid temperature ϑ must be given in °C for obtaining the relative change of volume, related to the initial volume at the base temperature of 20°C.

3.3 Initial spectral and weighted transmittance values of TEG

Besides the investigated thermodynamic and physical properties of TEG, its optical behaviour is crucial for realising the targeted Spectral Splitting filter. The result of the spectral transmittance measurement of TEG in its initial state at delivery condition, before exposing it to any stress test, is presented in Figure 6, black solid line. This characteristic is compared to the spectral transmittance measurement of distilled water (blue dot-dashed line) and to the ideal filter behaviour (green dashed line). The spectral irradiance of the AM1.5 spectrum ASTM G-173-03 (NREL, n.d.) is inserted in grey.

The weighted transmittance τ_{w1} of TEG for the wavelength range between 280 nm and 780 nm is calculated by 93.4 %, and τ_{w2} between 781 nm and 1100 nm is 88.1 %. The spectrum range beyond 1100 nm should be absorbed by the fluid, corresponding to low transmittance, but the calculation of τ_{w3} results in 33.0 %. This rather high value is caused by a local peak in the spectral transmittance that can be observed between 1200 nm and 1400 nm.

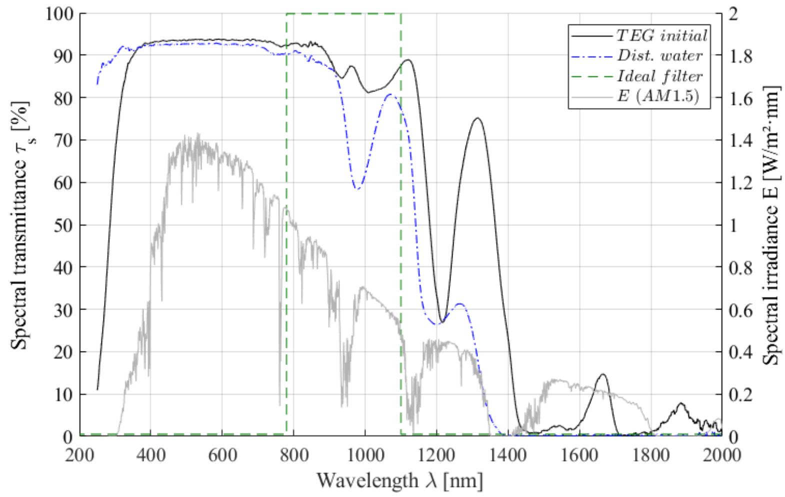

Fig. 6: Spectral transmittance measurement of TEG (initial state) and distilled water, in comparison with an ideal filter, referring to AM1.5 spectrum ASTM G-173-03 from NREL

3.4 Impact of long-term UV exposure on transmittance of TEG

The conducted exposure of eight TEG samples to an accumulated dosage of UV-light of 50 kWh/m² in the broad band between 300 nm and 400 nm results in only minor changes of the optical fluid properties. Figure 7 summarizes the spectral transmittance values τ_s for the reference sample “TEG initial” and the fluid samples extracted from the UV chamber in intervals of 100 h, respectively 133 h for the last one. Relevant changes of τ_s compared to the reference sample can be observed in the wavelength range below 400 nm, but no distinct trend with progressing test duration can be detected. In the spectrum range from 500 nm to 2000 nm, the spectral transmittance of all samples does not show noticeable deviation from the reference.

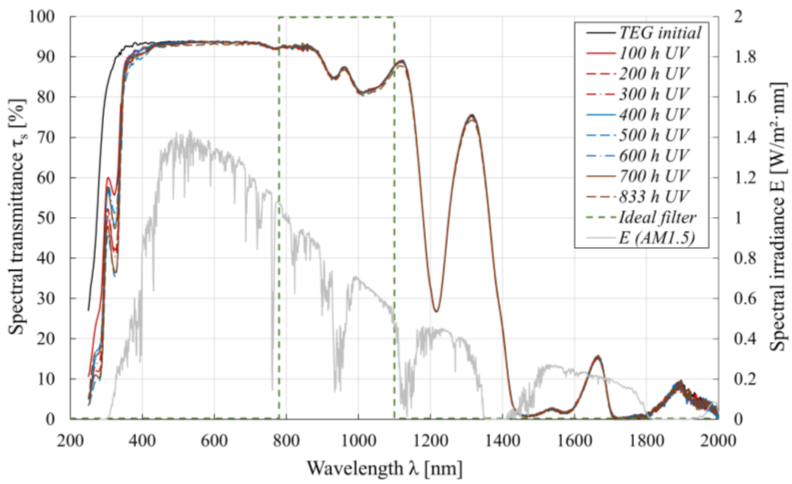

Fig. 7: Spectral transmittance measurements of TEG during UV exposure test in intervals of 100 h

Better quantification of the impact of the performed UV exposure test on the optical properties of TEG can be provided by comparing the weighted transmittance values τ_w before and after the measurement, separated for the three defined wavelength ranges, see Table 1. The absolute deviation of τ_w is between -0.5 percentage points (%P) and -1.2 %P, confirming that the UV exposure test with a dosage of 50 kWh/m² has negligible impact on the transmittance properties of TEG.

Tab. 1: Changes of weighted transmittance τ_w of TEG after 833 h UV exposure test

	τ_{w1} 280 nm – 780 nm	τ_{w2} 781 nm – 1100 nm	τ_{w3} 1101 nm – 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 833 h UV exposure	92.2 %	87.5 %	32.5 %
Absolute deviation	-1.2 %P	-0.6 %P	-0.5 %P

3.5 Impact of long-term high-temperature test on transmittance of TEG

The results of exposing 200 ml of TEG to high-temperature of 210°C ± 5°C for a duration of 700 h are revealed by Figure 8, showing the spectral transmittance τ_s for each extracted fluid sample in intervals of 100 h. The TEG was passivated with Nitrogen, which was refilled every time a sample was taken from the flask. The comparison to the reference curve "TEG initial" depicts a clear tendency of losing spectral transmittance in the spectral band below 780 nm with progressing test duration. By contrast, neither the wavelength range between 780 nm and 1100 nm, marked as "Ideal filter", nor the wavelengths beyond 1100 nm show major changes of τ_s.

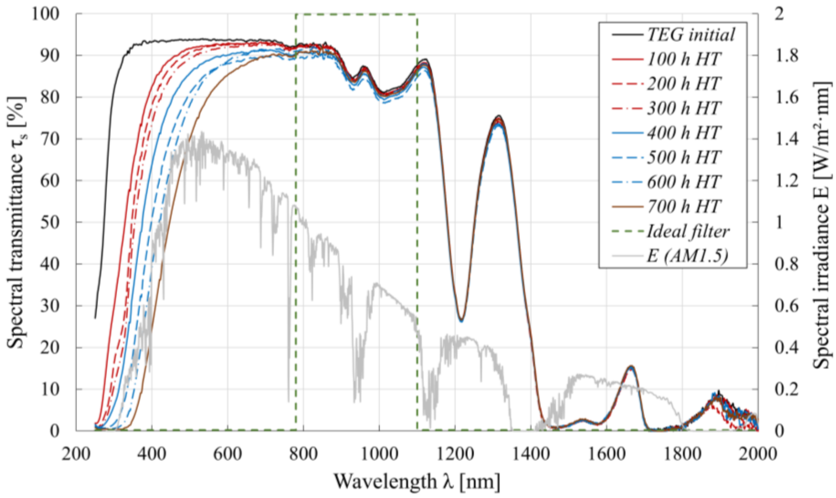

Fig. 8: Spectral transmittance measurements of N_2-passivated TEG during high-temperature test at +210°C in intervals of 100 h

These results are remarkably different if the TEG is not passivated by Nitrogen during the test. Figure 9 illustrates the spectral transmittance measurements of TEG samples from two different flasks that were tested simultaneously. In one flask, the remaining air volume was replaced by Nitrogen, while the other one was tested with air inside. Only the results of the test samples taken at 100 h, 400 h and 700 h are provided in Figure 9, both for the N_2-passivated TEG (red lines) and the air-filled flask (blue lines). Without passivation, the spectral transmittance τ_s of TEG decreases significantly after 700 h of high-temperature test, even in the spectral band between 780 nm and 1100 nm ("Ideal filter") that is important for the application of TEG in a Spectral Splitting CPVT receiver. Table 2 quantifies the impact of the performed high-temperature (HT) test by presenting the weighted transmittance values τ_w.

Tab. 2: Changes of weighted transmittance τ_w of TEG after 700 h high-temperature test for N_2-passivated and air-filled samples

	τ_{w1} 280 nm – 780 nm	τ_{w2} 781 nm – 1100 nm	τ_{w3} 1101 nm – 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 700 h HT-test, N_2-passivated flask	72.6 %	86.7 %	32.7 %
Absolute deviation, N_2-passivated flask	-20.3 %P	-1.4 %P	-0.3 %P
TEG after 700 h HT-test, air-filled flask	23.1 %	77.7 %	32.4 %
Absolute deviation, air-filled flask	-70.3 %P	-10.4 %P	-0.6 %P

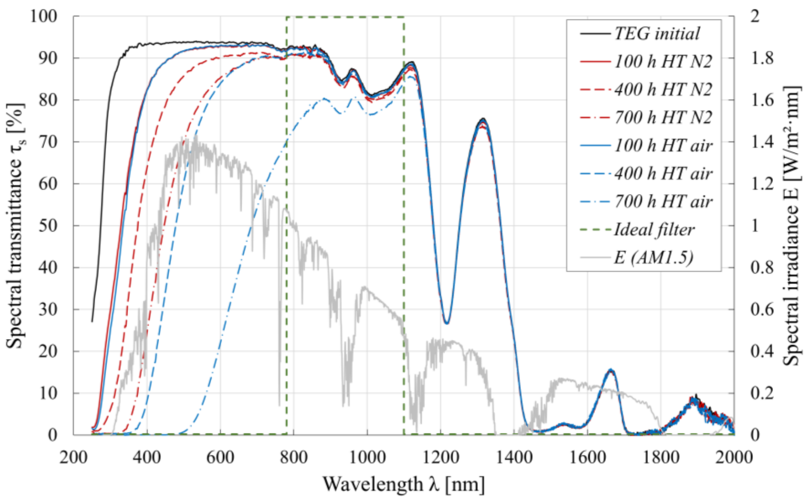

Fig. 9: Spectral transmittance measurements of TEG during high-temperature test, comparing air-filled fluid sample with N_2-passivated one

The results of the weighted transmittance values τ_w indicate that the performed high-temperature test has only minor impact on the optical performance of TEG in the wavelength band above 1100 nm. By contrast, in the relevant spectral band between 780 nm and 1100 nm, the decrease of τ_w is -10.4 %P for the air-filled flask, but only -1.4 %P for the N_2-passivated TEG sample. This effect of N_2-passivation becomes even more obvious in the spectral range below 780 nm, where the air-filled sample depicts a severe drop of τ_w by -70.3 %P.

3.6 Impact of long-term temperature cycling test on transmittance of TEG

The performed temperature cycling test between 45°C and 210°C fluid temperature for 180 cycles with a duration of 4 h each yielded the spectral transmittance results in Figure 10 for TEG passivated with Nitrogen. Again, samples of the fluid under test were extracted in intervals of 100 h for obtaining the corresponding spectral transmittance τ_s. The tendency with progressing test duration is comparable to the high-temperature test. A significant impact of this thermal stress on τ_s can be observed in the spectral range of short wavelengths below 780 nm, whereas the spectrum band above 1100 nm does not reveal any obvious change of τ_s. The relevant spectrum band between 780 nm and 1100 nm shows more degression of τ_s than it was observed during the high-temperature test.

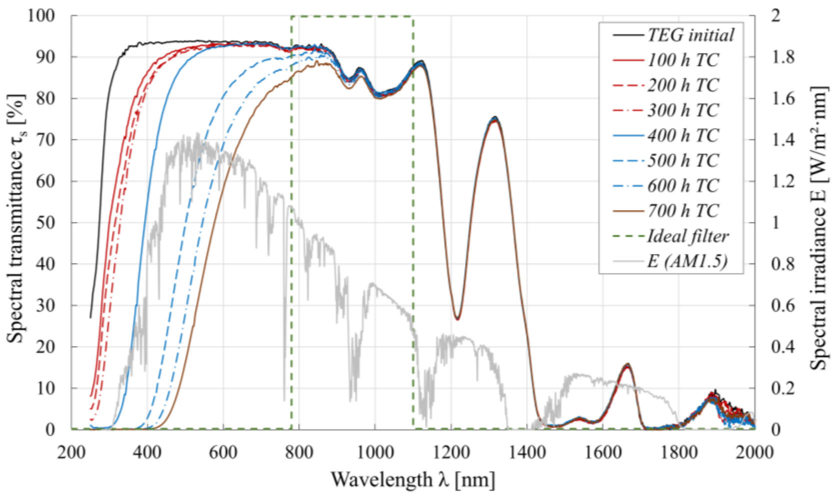

Fig. 10: Spectral transmittance measurements of TEG during temperature cycling test (+45°C to +210°C) in intervals of 100 h

The described tendency in the changes of τ_s can be confirmed by the calculation results of the weighted transmittance τ_w, see Table 3. The spectral band between 280 nm and 780 nm shows a considerable reduction of τ_w by -49.6 %P, whereas the change of τ_w in the upper spectral range between 1100 nm and 2000 nm is negligible. The important spectrum band between 780 nm and 1100 nm only reveals a moderate decrease of τ_w by -3.2 %P.

Tab. 3: Changes of weighted transmittance τ_w of N_2-passivated TEG after temperature cycling test

	τ_{w1} 280 nm – 780 nm	τ_{w2} 781 nm – 1100 nm	τ_{w3} 1101 nm – 2000 nm
TEG reference sample	93.4 %	88.1 %	33.0 %
TEG after 180 temperature cycles	43.8 %	84.9 %	32.9 %
Absolute deviation	-49.6 %P	-3.2 %P	-0.1 %P

4. Discussion and conclusions

The conducted investigation of Triethylenglycol revealed several findings that could be beneficial for its potential utilisation as heat transfer fluid in Spectral Splitting CPVT receivers.

The temperature dependency of the thermodynamic properties, density, specific heat capacity, dynamic viscosity and Prandtl-number are now available for TEG, both graphically and mathematically, for a temperature range up to 200°C. The derived approximation equations can be implemented in modelling approaches using TEG as heat transfer fluid. Especially the depicted characteristic of the dynamic viscosity η is important to consider, e.g. for engineering hydraulic systems with TEG, because it shows a significant decrease by a factor of 76 for a temperature rise from 20°C to 200°C. Furthermore, the thermal expansion of TEG is now described as a function of temperature. However, the mathematical description of the fluid parameters in the temperature range of 160°C to 200°C bases on an extrapolation of the supplier´s data, without being confirmed experimentally so far.

The optical behaviour of TEG in its initial state is satisfying, because it shows high values of weighted transmittance for the wavelength range below 1100 nm, as well as the desired stepwise decrease of transmittance towards longer wavelengths. Although, the weighted transmittance in the spectrum range above 1100 nm is not as low as expected.

The long-term exposure to UV-light with a dosage of 50 kWh/m² has minor impact on the optical properties of TEG. The weighted transmittance only decreased by -0.5 %P to -1.2 %P over the entire spectrum range.

By contrast, thermal stress reduces the transmittance of TEG significantly, but only in the spectrum range below 780 nm. In the considered Spectral Splitting configuration, the short wavelengths < 780 nm are absorbed by the solid filter anyways. Therefore, a reduction of the fluid transmittance in this spectrum band is acceptable, because it does not influence the overall filtering performance. Temperature cycles cause more degradation of the fluid than long-term high-temperature exposure, but the reduction of the weighted transmittance by -3.2 %P for 780 nm to 1100 nm is reasonable. If TEG is not passivated by Nitrogen but in direct contact with air when thermally stressed, the decrease of weighted transmittance values is accelerated significantly. Therefore, it is not recommended to use TEG for operating temperatures of 200°C in hydraulic systems that are open to atmosphere.

Triethylenglycol appears to be a suitable heat transfer fluid for utilisation in CPVT collector applications. Especially, because it provides the right spectral transmission behaviour that is requested for realising the approach of Spectral Splitting. The boiling point of 280°C offers a wide range of applicability, and the low safety requirements ensure an easy handling. The reliability of TEG in terms of temperature stress and UV exposure is confirmed by the performed investigations.

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