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Development and test results of a calorimetric technique for solar thermal testing loops, enabling mass flow and Cp measurements independent from fluid properties of the HTF used

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Abstract

Thermal heat transfer fluids (HTF) used in solar collectors (e.g. synthetic oils) are known to age and degrade [1]. This degradation is impossible to control, affecting the fluid heat transfer capacity and thus the ability of measuring the performance of an HTF heating device (e.g. a solar collector) based on known specific heat values.

Collector testing is also crucially dependent on an accurate measurement of HTF mass flow rate. Such measurement relies on flow meters suitable for the accuracy, operating temperature and flow range requirements of the testing procedures, often an expensive and demanding component in particular when no-intrusive measurements are to be done in a close circuit.

For power measurement purposes, as those performed in solar collector testing procedures, a direct measurement of the product between specific heat and mass flow rather than a separate measurement of both quantities is suitable. A calorimetric technique delivering this direct measurement is thus a suitable strategy to overcome such difficulties with acceptable (and even higher) measurement accuracy.

Solutions of this kind have already been proposed [2, 3]. In this paper we revisit and improve the solution presented in [2] and demonstrate its usefulness in a solar collector testing loop, for temperatures up to 200°C. A calorimeter prototype was thoroughly tested and calibrated with water as HTF (enabling accurate independent measurement of specific heat and mass flow rates values). Calorimeter calibration results were then used in the testing with thermal oil whose specific heat values were previously known from manufacturer and independent laboratory measurements.

A comparison of Cp measured by the calorimeter with the value given by the HTF manufacturer is used to test the calorimeter capacities. The agreement achieved was very good. It is noted that the technique can be easily implemented in any high temperature loops, large or small.

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1. Introduction

In solar collector testing a crucial measurement is that of the power being delivered by the collector P_{col} at any given moment and operating temperature (established as the average value between inlet and outlet temperatures), as in (1), where \dot{m} is the HTF flow rate through the collector and C_p its specific heat.

$$P_{col} = \dot{m}C_p(T) \times (T_{out} - T_{in}) \quad (1)$$

In testing loops using an HTF fluid other than water, the issue of flow rate accuracy is a more delicate one and in particular $C_p(T)$ is hard to know in any accurate fashion. Even when measured values are provided by the oil supplier, thermal oils tend to degrade with time and use and it is not practical (or even impossible) to keep on measuring its evolution with time.

A direct measurement of the product $\dot{m}C_p$ is proposed through the use of a calorimetric technique (Calorimeter) placed in series within the testing loop, where a known amount of power (electric power) is dissipated and inlet and outlet calorimeter temperatures are measured.

First $\dot{m}C_p(T)|_{cal}$ is obtained by finding the ratio $\frac{P_c}{T_{out}-T_{in}}$. The real value of $\dot{m}C_p(T)$ is then found by correcting with the calorimeter calibration factor F , according to (2)

$$\dot{m}C_p(T) = \dot{m}C_p(T)|_{cal} * F = \frac{P_c}{(T_{outcal}-T_{inca})} F \quad (2)$$

I.e. with (2) an accurate measurement of the product mass flow rate*specific heat is provided in any circumstances and type of fluid and eventual fluid thermal properties degradation or change, without having to know any details about that and avoiding complex calibration of fluid properties in loops with fluids that are not easily or cheaply disposed off and without having to resort to flow meter verifications with constant loop breakings and fluid sample retrievals.

The present paper is organized in the following way:

- In 2. a description of the calorimeter is made, highlighting its basic features and the care placed behind guaranteeing that the calibration factor F will be the same at any temperature.
- In 3. the calorimeter is inserted in a water testing loop, where both \dot{m} and $C_p(T)$ can be measured or are known with great accuracy and thus can be used for the determination of F
- In 4. the calorimeter was inserted in an oil loop and used to check the values of $C_p(T)$ given by the oil supplier. Coherent values are shown to result, and even only after a few hours of testing, fluid degradation (and C_p value changes) can be clearly observed, thus attesting to the great convenience of the new device developed and presented. An application to power calculation is also presented.
- In 5. the main features and conclusions are summarized.

Nomenclature

\dot{m}	mass flow rate in (kg/min)
$C_p(T)$	specific heat of the fluid at the average temperature $T = (T_{in} + T_{out})/2$ (J/kg.°C)
T_{out}	outlet temperature (°C)
T_{in}	inlet temperature (°C)
P_{col}	power collected by a solar collector (W)

P_c	dissipated power in calorimeter (W)
T_{outcal}	calorimeter outlet temperature (°C)
T_{inca}	calorimeter inlet temperature (°C)
F	calorimeter calibration factor
ρ	density of water (kg/l)
IC	inner chamber
OC	outer chamber
HTF	heat transfer fluid
PT	parabolic through
a, b	constants of a linear least square fit

2. Calorimeter, concept and description

In [1] the problem of HTF degradation in PT concentrators performance testing and evaluation was raised and in [3] a concept for a calorimeter like technique was developed to overcome these type of difficulties. However this calorimeter is complex and there are other, hopefully simpler, possible designs.

In prior work [2], a calorimeter technique very similar to the one presented in this paper, had already been proposed and developed, precisely to solve this problem. The configuration chosen for the new device described in the present paper is an improvement on that earlier one with the following objectives:

- maximize heat input to the circulating fluid
- minimize and, above all, render as constant as possible the heat loss to the surroundings at any operating temperature

The concept is the following (see Fig.1):

- in a stainless steel cylindrical inner chamber (IC) heat is provided by an electrical resistance immersed in the HTF
- this chamber is inside another stainless steel cylindrical chamber (outer chamber- OC) from which the HTF fluid comes; this outer chamber provides an environment for heat losses which is at the inlet temperature to IC; thus the power which is lost to the fluid, is very much the same at any temperature at which the calorimeter is to be used.

An adequate design (see Fig. 1) ensures that the fluid really fills IC and bathes as much as possible the electrical resistance (note the use of the long cylindrical baffle inside IC and observe the way the fluid comes in and gets out of IC). Nevertheless IC chamber is insulated (2.5cm of rock wool) and so is the OC external well (3cm of rock wool).

The calorimeter is instrumented with inlet and outlet 4-Wire PT100 temperature probes and power is measured through the voltage across the calibrated electrical resistance used. Dissipated power is to be chosen according to the recommended flow rate for solar collector testing ($0.02 \text{ kgs}^{-1}\text{m}^2$ [4]) and HTF temperature differences (usually ranging from 5°C to 15°C). In the case of the device developed and analyzed an electrical resistance of 28.8Ω was chosen.

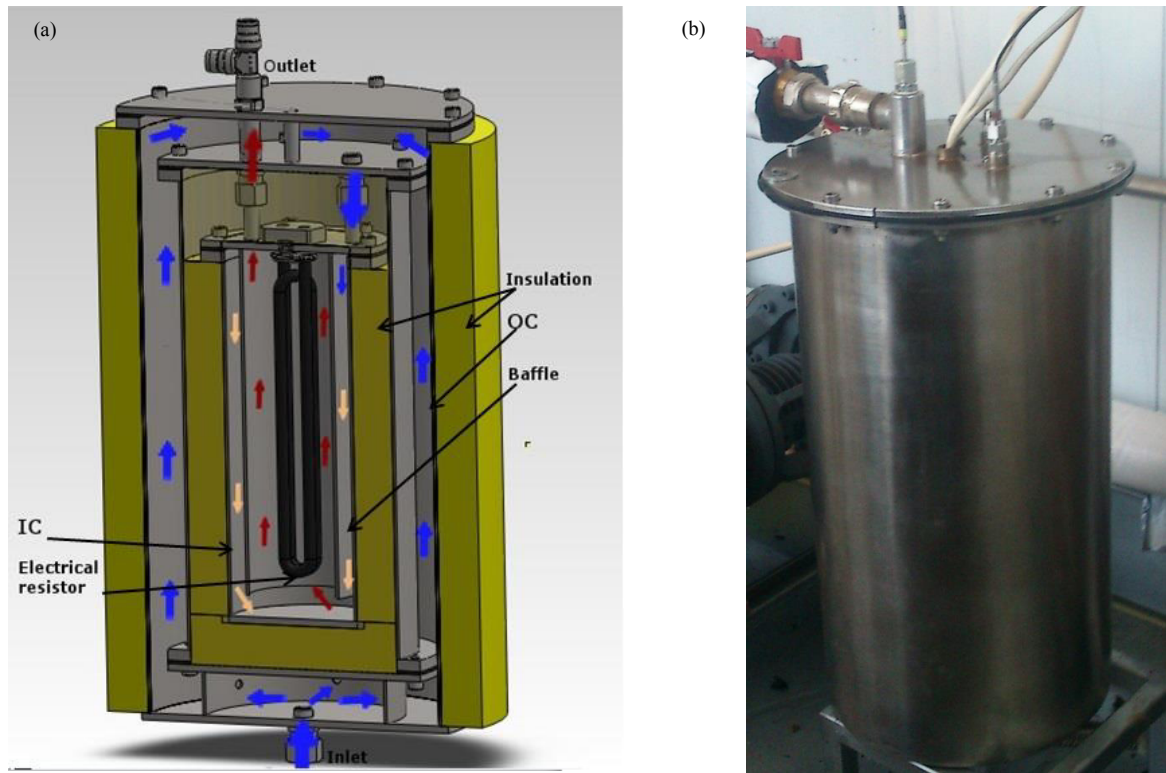


Fig. 1. (a) cross section of the calorimeter; (b) photograph of the calorimeter fully assembled, but without the insulation of the OC in place.

3. Calibration with water – factor F: the calorimeter equation

3.1. Testing circuit

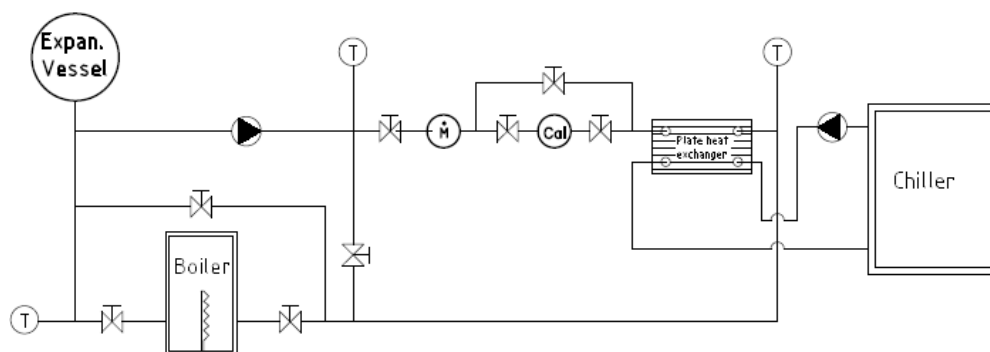


Fig. 2 the testing circuit

In the circuit used, water is circulated as the HTF and heated by an electrical boiler, constituted by an 100 liter tank with a 6kW electrical resistance inside. Inlet temperature to the calorimeter is kept constant (within 0.1°C) with

the help of an heat exchanger and cold water provide by a chiller.

Flow rate is very accurately measured within 0.2% by a electromagnetic flow meter, calibrated at the solar collector testing laboratory [6] and CP is calculated by [5] as function of temperature T as in (4)

$$C_p = 4218,525 - 2,55222T + 5,51766E^{-2}T^2 - 4,9454E^{-4}T^3 + 2,3426E^{-6}T^4 - 3,79E^{-9}T^5 \quad (4)$$

Since in the case of water the flow meter used is a volumetric one and it is also necessary to convert volume flow rate to mass flow rate by considering (5), which gives the density of water ρ as a function of temperature

$$\rho = 1 + 0,0000117T - 0,0000059T^2 + 2,008E^{-8}T^3 - 3,897E^{-11}T^4 \quad (5)$$

Flow rate values and stability are insured by a frequency inverter associated with the circulation pump.

Flow rates from 0 to 5 kg/min could thus be achieved and testing made for inlet temperatures from 25 to 85°C.

3.2. Methodology used

For each temperature and for different flow rates, and using (2) one would expect:

$$\dot{m}Cp(T)|_{real} = \dot{m}Cp(T)|_{cal} * F \quad (6)$$

Several pairs of \dot{m} values were obtained with the calorimeter and by measuring independently \dot{m} with the flow meter, for each temperature and for different flow rates.

The values chosen were ~1, 2, 3, 4 Kg/min for the flow rate and ~45, 65, 80°C for the mean temperature in the Inner Chamber (IC).

Results were plotted and a straight line regression (least square fit) was obtained of the form

$$\dot{m}Cp|_{real} = a \times \dot{m}Cp|_{cal} + b \quad (7)$$

Where $\dot{m}Cp|_{cal}$ was measured according to

$$\dot{m}Cp|_{cal} = \frac{P_c}{(T_{outcal} - T_{inca})} \quad (8)$$

And $\dot{m}Cp|_{real}$ from the product of \dot{m} as measured by the flow meter and Cp calculated from (4).

If $b=0$ had been chosen then $a=F$. A careful analysis of all the results leads to the choice of a regression with $b \neq 0$, as the one that minimizes the errors at all temperatures.

Thus (8) will now be addressed as the calibration equation for the calorimeter,

3.3. Results for the calorimeter equation

Results are plotted in Fig. 3.

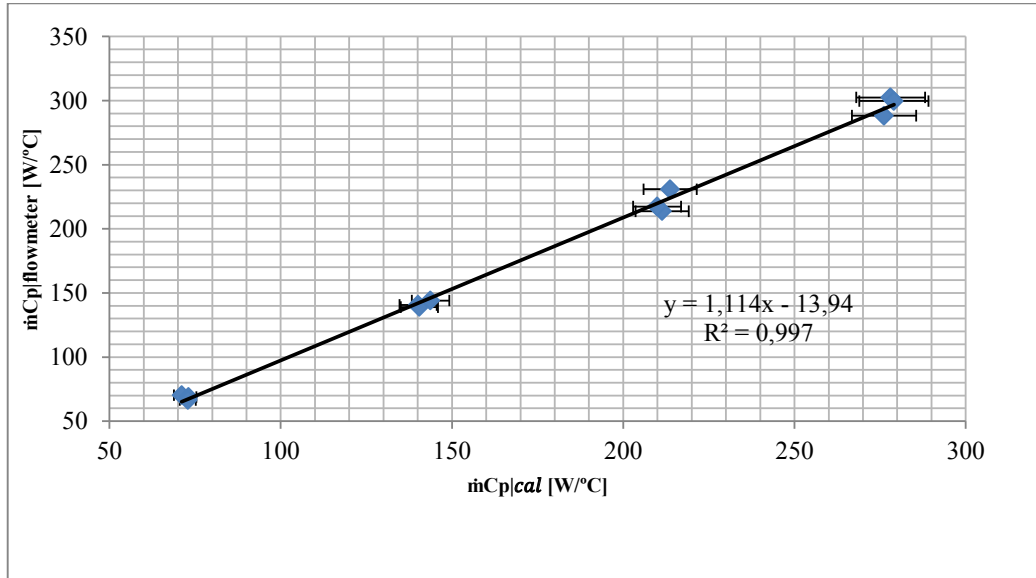


Fig. 3 : flow rate as measured by the flow meter vs flow rate as measured by the calorimeter, for different fluid temperatures (45,65,85) , as evidenced by the cluster of points around the approximately chosen flow rate values 1, 2, 3, 4Kg/min

The least square fit to the measurement points produced:

$$\begin{aligned} a &= 1.114 & \delta a &= 0.018 \\ b &= -13.94 \text{ W/}^{\circ}\text{C} & \delta b &= 3.55 \end{aligned}$$

Fig. 4 also shows the error bars associated with each measurement of $\dot{m}Cp|_{cal}$; it also shows (although they are barely perceptible) vertical error bars (corresponding to 0.2% of the absolute value resulting from the flow rate measurement)

The uncertainties δa and δb result from the least square fit considering all uncertainties involved.

Note: It can be seen that b is not zero, albeit with a small value. It is the result of a mathematical imposition but perhaps reflecting some thermal characteristic of the calorimeter not discussed here.

The results obtained show that an upper limit for the accuracy is somewhere between 3 and 4%. This accuracy is certainly susceptible of improvement through the measurement of the dissipated power, since there were problems in the measurement of this quantity, not only because current was not directly measured but also because local voltage was far from a pure sinusoidal. Correcting for these conditions will likely yield accuracy at least between 1 to 2% . Further improvements might even be achieved through the use of a DC current source.

4. The calorimeter in the oil loop; application to the measurement of the CP of oil

4.1. The oil loop

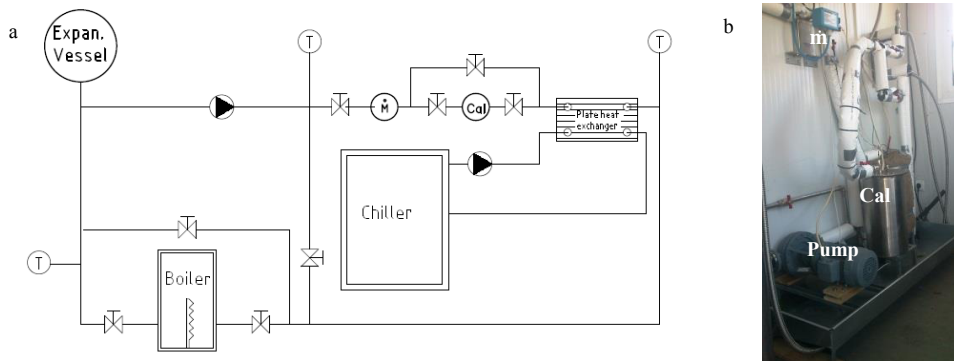


Fig. 4 shows: (a) a scheme of the oil loop, very similar to that of Fig. 2; (b) a photograph of the setup, with the calorimeter inserted and signaled, with OC not yet insulated

The oil loop is conceptually the same as the water loop. The direct flow rate measurement is made with a Coriolis force based flow meter [Rheonik RHM04].

All the other components in the loop are the same as in Fig. 2.

4.2. Application to the determination of the oil C_p at different temperatures

With the calorimeter calibrated (Section 3,) it would now be possible to use it as planned, for the direct measurement of the product $\dot{m}C_p(T)$ of any HTF in a solar collector testing loop.

As an application it was decided to use the calorimeter to measure $C_p(T)$ and compare the results with those provided by the oil supplier.

Measurements were made from 45 to 155°C using the oil loop of Fig. 4, charged with a given fluid (BP Transcal N).

Eq. (2) was modified to yield

$$C_p(T)|_{real} = \frac{1}{\dot{m}|_{coriolis}} (\dot{m}C_p(T)|_{cal} \times a + b) \quad (9)$$

According to the supplier $C_p(T)$ varies with (T) in a linear fashion as in (10)

$$C_p(T)|_{supplier} = 3.571T + 1807.6 \quad (10)$$

4.3. Results

From (11) it can be seen that the C_p of the oil HTF is lower than that of water, which means that the same amount of power being dissipated in the electrical resistance will now yield a higher temperature difference between inlet and outlet to the calorimeter. This fact was taken into consideration.

Since C_p varies with T , the results will have a built in inaccuracy due to the temperature difference across the calorimeter. For the high flow rate value of 5kg/min, this temperature difference is on the order of 7-8°C and on the order of 17-20°C for the lowest flow rate of 2kg/min. All results are listed in Table 1.

The empty cells in Table 1 correspond to the fact that very high flow rates were impossible to obtain at low

temperatures and, for higher temperatures, the low flow rates were not used so that outlet temperatures would not exceed the present setup temperature tolerances.

Table1. Summarizes the results obtained at different temperatures

T (°C)	65	85	105	115	125	135	145	155
Cp Cal at ~ 6kg/min [J/kg.°C]	-	-	-	2258	2242	2316	2395	2521
Cp Cal at ~ 5kg/min [J/kg.°C]	2094	2199	2204	2203	2159	2362	2241	2530
Cp Cal at ~ 4kg/min [J/kg.°C]	2137	2194	2179	-	-	-	-	-
Cp Cal at ~ 3kg/min [J/kg.°C]	2151	2166	2234	-	-	-	-	-
Cp Cal at ~ 2kg/min [J/kg.°C]	1910	2013	2020	-	-	-	-	-
Cp Supplier [J/kg.°C]	2038	2108	2174	2214	2256	2290	2322	2364

Fig. 5 is a plot of the results obtained, as they appear in Table 1, showing error bars associated with each measurement and the information (straight line) given by the supplier

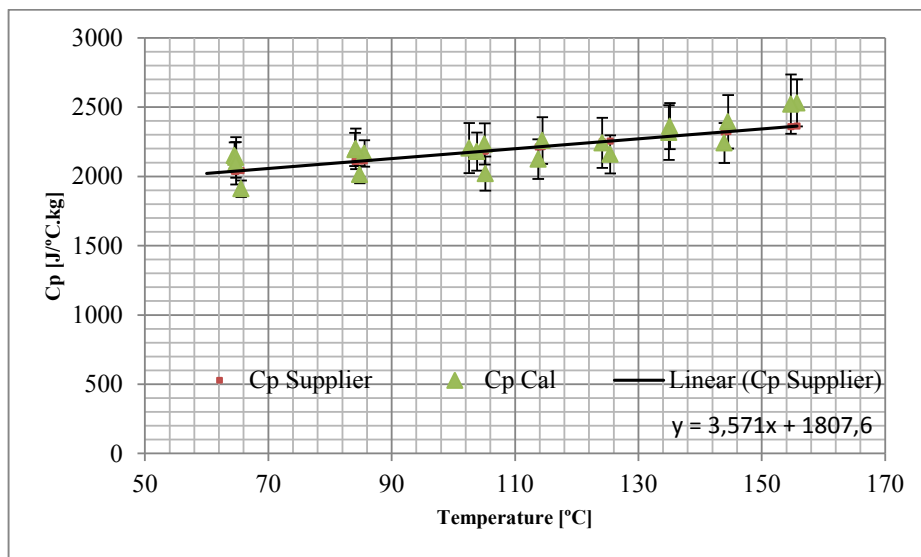


Fig. 5; Cp as function of T; (1) dots with error bars are the results from the calorimeter (2) straight line: Cp given by the supplier

These results shows that the values obtained are in good agreement with those provide by the supplier, even though in the case of the calorimeter, and as was explained, the fluid is not at an exact, fixed temperature as it is assumed in the supplier's curve.

For the highest temperature (155°C) there is perhaps a tendency for a larger deviation of the measured value from that of the supplier's curve, which is in part attributed to the difficulty in achieving thermal stability and tolerances in the experimental setup

Fig. 6 contains two pictures, those of two oil samples: (i) oil which had been used in all the tests referred above and which was labeled as "used oil" and (ii) "new oil" out of the supply barrel.

It can be seen that new and used oil look different, but no change (after several hours of operation) is already really perceptible in terms of $C_p(T)$ as measured by the calorimeter. In future work $C_p(T)$ will be independently monitored for the used oil and the corresponding calorimeter's response will be analyzed as a further test of its accuracy and usefulness.

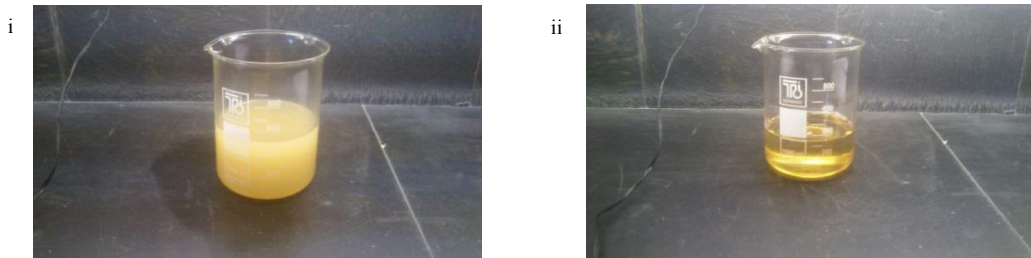


Fig. 6: (i) a sample of “used oil” (ii) a sample of “new oil”

5. Conclusions

A new calorimeter was developed and tested to provide an accurate measurement of the product, $\dot{m}C_p$, i.e flow rate times specific heat together, an essential part of any solar collector efficiency measurement using an HTF other than water.

This device is very simple, cheap and easy to build, and provides a degree of accuracy which is not easily matched by that of the standard method, which requires constant sampling and external control measurement of the C_p of the HTF. It is based on the principle of delivering a known amount of power to the circulating fluid, in a way that the power lost to the environment is a small quantity of the total and, more important, nearly the same at any operating temperature, thereby determining a simple and unique constant calibrating factor.

Besides, all relevant measurements can be made with very common and simple measuring instruments (amp meters and voltmeters!), dispensing with the expensive flow meters and their calibrations used in this investigation.

The calorimeter was fully described and its calibration equation was determined with the help of a low pressure water loop. The calorimeter was then inserted in a thermal oil loop and used to measure the C_p of the circulating oil. The results obtained show a good agreement with the values of $C_p(T)$ provided by the supplier, an indication of the calorimeter's performance.

This calorimetric technique can be easily implemented with any type of HTF fluid, in large or small loops, for simple online performance evaluation or for collector testing and certification.

The development presented in this paper was limited to temperatures below 180°C simply because the oil loop used was of the atmospheric type and some of the components (flow meter, pump, etc) could not take temperatures above 200°C. However the concept (mechanical construction and thermal behavior of the calorimeter) can certainly be applied to higher operating temperatures and it should operate equally well. However thermal properties of the fluid may not enable sufficient heat dissipation from the electrical resistance towards it, therefore forcing the adoption of suitable modifications of the inner chamber and resistance type and size (IC).

In future work, a device developed with the concern of achieving the highest possible accuracy will be developed and even proposed as a product to be made available on the market

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