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Experimental Methodology and Thermal Loss Tests on Small Size Absorber Tubes for Solar Applications

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Abstract: Since thermal energy for residential applications is a relevant part of the entire energy demand, solar technologies could play an important role in decreasing fossil fuel consumption. A novel small parabolic trough collector matched with a storage system is developed to satisfy heating and required hot water demand for a single house. A new receiver concept is designed and a prototype is realized using two coaxial tubes (three spattered layers). A covering glass with vacuum inside completes the high tech design. Because of numerous innovations including the small size, a specific off-Sun measurement procedure is set up with the aim of evaluating the real thermal loss and direct heating of the absorber by Joule effect. A novel test procedure is proposed for the one-end absorber. The receiver performance results are reported under vacuum conditions and with air at ambient pressure.

Keywords: micro parabolic trough collectors; thermal loss absorber; test rig; renewable sources; solar collectors for residential applications

1. Introduction

The energy use in residential applications involves a significant fraction (more than 1/3) of the total requested supply for human activities [1]. Renewable sources can play an important role in reducing the consumption of conventional fuels. A good integration of the technologies with houses' facilities is a target to make them more effective and competitive. Solar systems are one of the most favourable to meet residential needs (matched with energy storage components) and beside this, the market for PV panels and flat thermal collectors has grown widely in the last decade.

Up to now, almost all concentrating solar technologies had been limited to large installations in order to produce electricity [2–8]. Over the past decade, several types of studies have been done on the standard size parabolic trough collectors (PTCs) and their thermal loss. These standard size PTCs, owing to their large scale, have numerous standard test setups for thermal loss measurement. The measurement of the heat loss can be performed using various modes such as steady state equilibrium, quasi steady state equilibrium and surface temperature measurements [9].

Price et al. [10] reported a field study of the in-situ thermal performance of parabolic trough receivers by using an infrared camera. Eichel et al. [11] reported the heat losses of single parabolic trough receiver components under steady state conditions using optical non-destructive measurement techniques at Schott, DLR and NREL and the results showed a reasonable agreement between he different measurement setups.

During the last five years, Balghouthi et al. [12] have reported optical evaluations of medium temperature (80–250 °C) parabolic trough solar collectors using photogrammetric techniques and also the heat losses and thermal efficiency evaluation of medium temperature PTCs. Under summer Sun irradiation and with a clean reflector surface the thermal efficiency reached 0.43, which was determined under steady state conditions according to the ASHRAE 93-1986 (RA 91) norms. Caron et al. [13] reported that by measuring in-situ the heat loss of a parabolic trough receiver using transient infrared thermography the result precision range is below ±10% for all tested receivers under field test conditions in comparison to reference steady-state heat loss measurements under laboratory conditions. Navarro-Hermoso et al. [14] reported a novel laboratory test bench for the integral characterization of PT receivers. This novel method determined the global efficiency of a receiver independently from the optical absorbance of the internal absorber, the tube optical transmittance of the external glass envelope and the heat losses of the receiver and could be used to evaluate heat losses of new types of receivers and they summarized the testing procedure and validation of a methodology for large size PTC collectors installed in solar thermal power plants. Jamal-Abad et al. [15] reported the heat transfer and thermal efficiency of a PTC absorber filled with copper foam (a porous medium) based on the ASHRAE 93-1986 (RA 91) standard. The report showed that by using the porous medium the overall loss coefficient was reduced by 45% and results in less energy losses and better efficiency in comparison to standard PTC collectors. However, even though many studies have reported thermal loss measurements of standard PTCs, there has been very little research reported on other PTC designs.

Up to now only very limited studies exist for small size PTCs and their thermal loss measurements. Bin Zou et al [16] studied a small-sized PTC (2 m length of the receiver tube) for water heating in cold areas and reported that the thermal efficiency reached about 67% (for solar irradiation lower than 310 W/m^2). Visa and Duta [17] studied a novel flat plate solar thermal collector with un-conventional shape for facade integration, increasing the output and durability of the flat plate solar thermal collectors through adaptive tracking by considering the main barriers that limit the large scale implementation of solar-thermal systems for urban applications. However, there is no specific study on PTC applications in urban area. Abbood et al. [18] reported the thermal performance of a small and lightweight locally designed PTC according to the ASHRAE 93-1986 (RA 91) standard.

Previous studies about the efficiency, feasibility, evaluation and analysis of small size PTCs, specially considering their thermal application in urban areas are poor. The main purpose of the present study was therefore to measure the thermal loss in a micro-parabolic trough collector (m-PTC). For this reason, a m-PTC was specifically designed with the aim of fully integrating it in the roof of either a single house or a block of apartments. The main advantage, with respect to the non-concentrating ones, is the possibility to reach higher temperatures in short time intervals increasing the amount of energy of the heat transfer fluid. That energy could also feed a bottoming small-scale Organic Rankine Cycle (ORC) system for cogeneration or an absorption chiller for air cooling purposes. First of all, the design of the m-PTC has started from the development of optical and thermal models with commercial software (ZEMAX and COMSOL Multiphysics). Some of the physical quantities of interest (such as mechanical tolerance and material properties) were set by the datasheet of specific available components and literature data. Consequently, several parametric analyses have been conducted to define an optimal collector geometry configuration. The experimental procedure reported in this article supports previous design processes with the verification of some of the boundary conditions used.

2. The Components and Experimental Set up

2.1. The Absorber Tube

The new receiver is developed for concentrating solar radiation in a small-size parabolic trough collector (1800 mm long with an aperture of about 420 mm). A novel geometry solution is considered; two concentric copper tubes are inserted in an evacuated glass envelope so that the fluid inlet and output are at the same side of a one-end receiver (Figure 1).

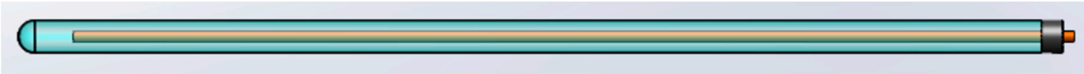


Figure 1. The scheme of the one-end receiver tube for m-PTC.

This geometry solution offers some advantages in respect to the standard one, in which the fluid passes through the tube from one side to the other—by accepting a little higher drop in pressure it is much simpler and also more economical to build. In fact, one closed edge is realized just by sealing the glass on itself during the crystallization and the glass-to-metal junction is applied on one side. Decreasing the number of those elements, which represent a critical aspect for solar absorbers in general, also lead to reduced risk of losing vacuum conditions under long term use. The receiver tube has a diameter of 10 mm (1 mm thickness), with a selective absorber (Cermet) in order to increase the energy absorption in visible range while reducing the emission in (the) infrared range ($\alpha = 0.94$ and $\varepsilon = 0.13$ at ambient temperature). A smaller tube is used with an internal diameter of 5 mm (0.5 mm thickness) to feed the receiver with a countercurrent fluid. Four springs support both pipes in the glass cylinder and keep them aligned in the reflector focus. Even if the operating temperature is supposed to be lower than that for the standard PTC (180–250 °C maximum), the vacuum level is fixed at 10^{-4} mbar.

2.2. Test Procedure and Test Rig

Since many new features such as small size tube are introduced in the receiver, some specific experimental tests are required. They would prove the "bona fides" of the modeling process but also, most importantly, the manufacturing quality of components and overall performance.

The absorber is designed starting from a 3D optic-thermo-fluid dynamic model. There is no reference to verify its real performance numerically because the adopted technical solutions are not standard. Consequently, a specific test bench should be set up; an off-Sun mode analysis is considered in order to distinguish the different physical phenomena. Because of the small size of components and the novel inlet/outlet configuration, the layout proposed in [9,19–21] was not suitable in this case: for instance, there is no place to insert many sensors and more than one cartridge heater to guarantee uniform temperature along the absorber. Therefore, a novel testing method is proposed as shown in Figure 2: the internal pipe is replaced with a copper bar, which is insulated by a dielectric sleeve. However, the end of bar is supposed to be in contact with the external tube to create an electrical circuit so that two different poles (negative and positive) could be located at the beginning of the system. In this configuration, Joule effect could be generated directly using a dual power supply (controlling current and voltage separately).

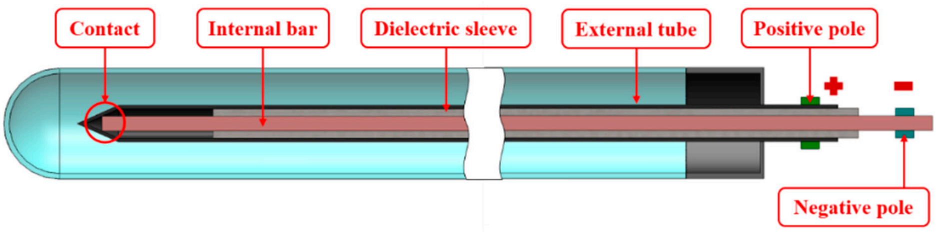


Figure 2. Scheme of the electrical branch made with the external tube of the receiver.

The copper bar used should have a similar electrical resistance as the receiver (similar geometric section and material) in order to amplify the heating effect and keep it uniform alongside the absorber tube. However, the global resistance is expected to be in the order of mΩ that means the power would be supplied at very high current (hundreds of Amperes) and low voltage (near unitary). Since no laboratory device is able to supply this condition, it was necessary to provide a specific power generation unit, an alternative current loop (AC-Loop), based on a transformer (1200 W at 2.5 V and

500 A). Furthermore, a Variac should be used to accurately regulate the voltage to the transformer input (Figure 3).

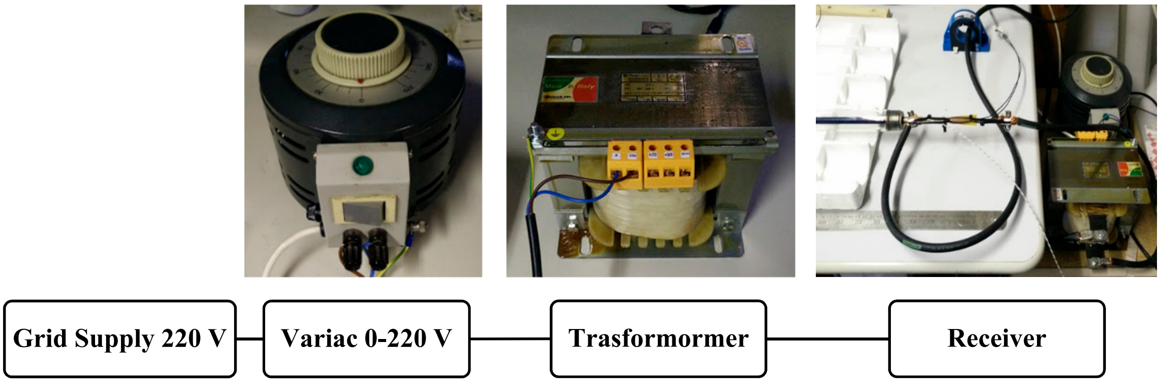


Figure 3. Variac, transformer, supply chain and connection scheme to the grid.

Several sensors are necessary to monitor and measure the main characteristics of the system:

- A Hall effect transducer for the supply current (calibrated with an error <0.1% MV);
- Temperature sensors arranged as in Figure 4 (a type T thermocouple and two resistance temperature detector (RTDs)).

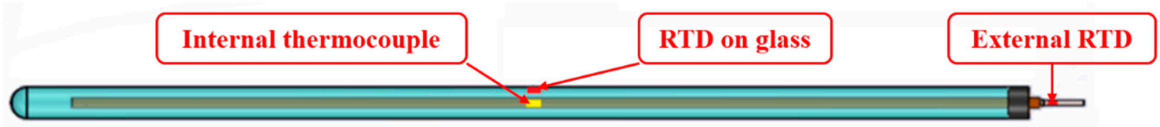


Figure 4. Position of the three temperature sensors.

In this case, only one thermocouple could be used inside the receiver tube. It is fixed around the dielectric sleeve and the small clearance between receiver and copper bar guarantees the contact with the internal surface of the outer tube. Obviously, allowing geometries, it would be convenient to use different temperature sensors in various axial positions. The flat RTDs are located at the beginning of bar and above the glass cylinder at about 1 m from the inlet.

Furthermore, two DAQ systems are used to acquire the overall signals and voltage in the circuit with a global error <1% MV.

3. Test Procedure, Calibration and Experimental Results

3.1. The Absorber Tube

Some preliminary test should be conducted to verify the value of electrical resistance between two poles calibrating the overall system and sensors. This is also necessary to calculate the input power (using Equation (1))

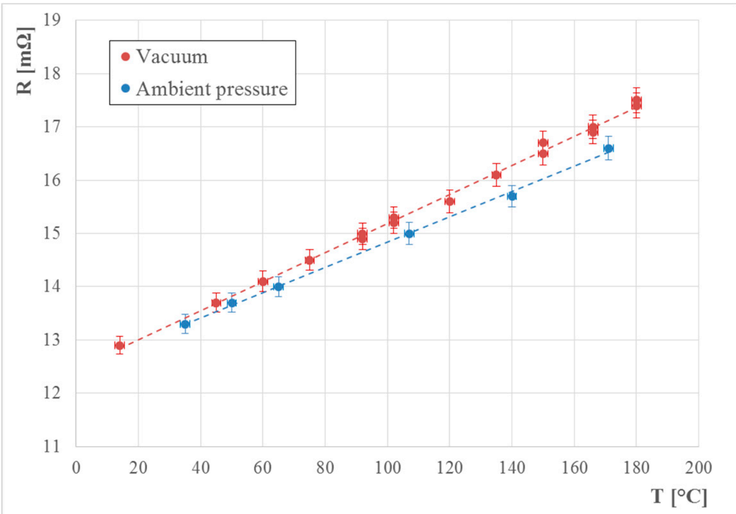
$$P_{in} = R \cdot I_{rms}^2 \text{ [W]} \tag{1}$$

where R is the resistance and I_{rms} is the peak current. The resistance should be measured in the stabilized temperature of tube at different levels (up to 180–250 °C). The procedure to be followed is:

(a) use the AC-loop to reach the desired temperature;
(b) keep temperature stable for at least some minutes;
(c) disconnect the AC-loop supply and use a high-accuracy laboratory power supply to feed the system at fixed current (a 6–8 digital unit is applied);

(d) measure the output voltage imposing 1 A dc under stationary conditions (for about 10 min obtaining: $R(T) = V_{DC\ out}/I_{DC}$ [Ω]).

The data should be recorded at least every second and the test is performed until the absorber temperature is within the accuracy of (the) thermocouple (±1 °C). Afterwards, some filtering and average operation are necessary to finalize the overall system calibration. In Figure 5, the reported results show a linear trend for both the conditions of absorber tube i.e. vacuum condition and with air at ambient pressure. For the first case, the measurements were conducted by increasing and decreasing the temperature in order to avoid hysteresis phenomena (it is found to be at least 1%, within the accuracy of the system); for the later one, the variation of the electrical resistance with temperature must be verified again to ensure the uniform temperature distribution along the tube The trends in Figure 5 confirm a similar behavior for both cases and the sensitivity varies under 3%, closed to measurement errors.



Vacuum	
T (°C)	R (mΩ)
14	12.9
45	13.7
60	14.1
75	14.5
92	14.9
102	15.3
120	15.6
135	16.1
150	16.5
166	16.9
180	17.4
180	17.5
166	17
150	16.7
135	16.1
102	15.2
92	15
75	14.5
60	14.1
45	13.7

Ambient pressure	
T (°C)	R (mΩ)
35	13.3
50	13.7
65	14
107	15
140	15.7
171	16.6

Figure 5. Electrical resistance as a function of the inside temperature of the receiver.

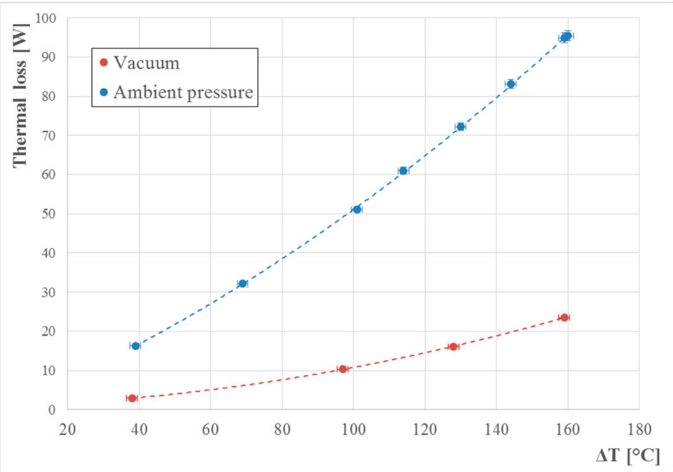
3.2. Thermal Loss Evaluation

For every stationary interval, the equilibrium rms current is recorded and relative resistance derived. Consequently, Equation (1) gives the power supplied due to Joule effect that is equal to thermal loss.

In Figure 6 thermal loss is shown as a function of the difference between receiver internal temperature and ambient temperature. The variation from vacuum to ambient pressure condition (the same tube is used) seems to be consistent; the maximum loss reaches 23.5 W in the first case, while it rises up to 95.4 W in the other one, at 180 °C. In other word, the thermal loss under ambient pressure conditions is four times higher than under vacuum conditions.

The variation of the boundary temperature values (the inlet RTD and the one in contact with glass) was also monitored (Figure 7): it could be seen how they increase with the internal temperature, especially without vacuum, but the presence of the glass envelope acts as a shield for the absorber anyway. The RTD at the inlet, indeed, did not reach 100 °C when the tube was stabilized at 180 °C inside. The glass temperature remained under 30 °C in the case of vacuum; otherwise, it raised up to 60 °C.

As reported before, the design of the collector was based on optical ray-trace simulations with Zemax and thermo-fluid dynamic CFD analysis with Comsol Multiphysics (Comsol Multiphysics 5.3a, COMSOL Co., Ltd., Stockholm, Sweden). An optical analysis has been conducted to optimize the mirror parameters (rim angle and aperture of the parabola, optical errors, etc.). The results of the optical analysis and the solar flux distribution on the absorber tube have been used as boundary condition for the numerical model of the receiver tube. A 3D FEM model has been developed in order to analyse the relevant physical characteristics and to predict the performance of the receiver. The thermo-fluid dynamic model of the receiver tube is able to describe the dynamics of the fluid inside the absorber tube and the heat transfer between all the components of the receiver.



Vacuum				
T int [°C]	T amb [°C]	ΔT [°C]	P [W]	Err. [W]
60	22	38	2.9	0.0
120	23	97	10.3	0.2
150	23	128	16.1	0.2
179	20	159	23.5	0.3
210	22	187	33.5	0.5
240	23	217	46.0	0.6

Ambient pressure				
T int [°C]	T amb [°C]	ΔT [°C]	P [W]	Err. [W]
60	21	39	16.3	0.2
90	21	69	32.1	0.4
120	19	101	51.1	0.7
135	22	114	61	0.8
150	20	130	72.2	1.0
165	22	144	83.1	1.1
180	21	159	94.9	1.3
		160	95.4	1.3

Figure 6. Thermal loss vs. the difference between the internal and ambient temperature.

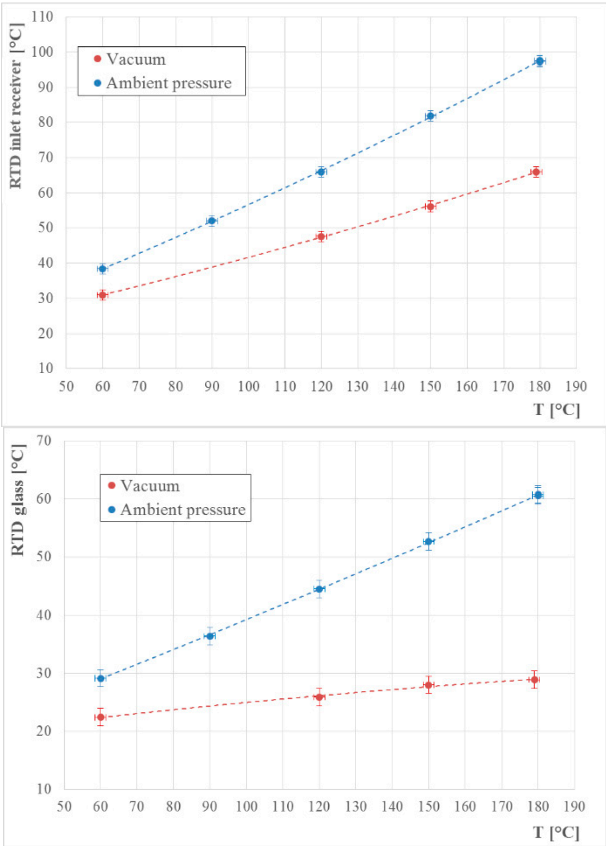


Figure 7. Temperature of the inlet receiver and the glass envelope for different internal temperature.

In any case, the physical models can also predict the performance of the collector starting from some assumptions which have to be validated. Therefore, the measurements of heat loss and temperature are used to calibrate and upgrade the initial numerical simulations matching the results. The main analysis is focused on the emissivity of cermet layers covering the copper receiver since it is the main responsible parameter for thermal loss in vacuum conditions. Two test results are taken as reference (absorber tube temperature at 60 °C and 180 °C) and the experimental data is coupled implementing in the model the values for emissivity 0.138 and 0.208 respectively (a raise of 50%). Starting from them, the test temperature conditions were imposed in numerical simulations finding that the emissivity would not remain constant. Equation (2) gives a linear behavior with receiver temperature is verified instead, in the range of interest:

$$e = 0.070 \cdot T + 0.068 \tag{2}$$

where e is the emissivity and T is the receiver temperature. The results of using this function are reported in Figure 8. All the values for the thermal loss are well predicted with a maximum deviation under 1%.

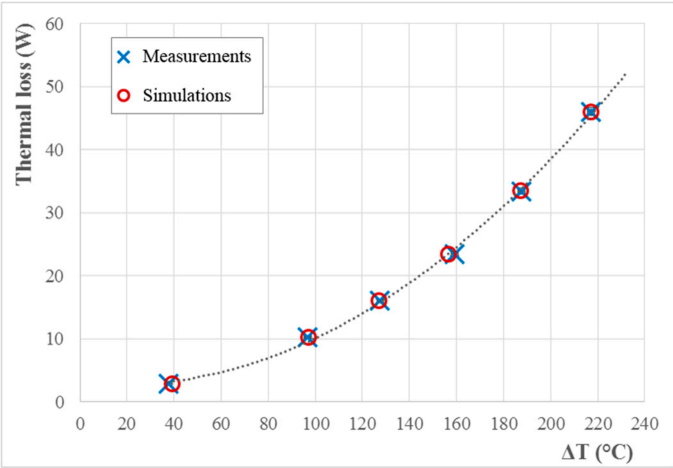


Figure 8. Comparison between test and computational results.

Afterward, it would be possible to evaluate the performance of the receiver tube in details extending the analysis to different configurations and boundary conditions.

4. Conclusions

Laboratory testing of the novel small-size PTC components is necessary to anticipate the performance of the overall system under operating conditions. A specific setup has to be arranged to characterize the receiver concerning thermal loss as a function of the internal temperature. Standard test procedures are not suitable because of the dimensions of system. In this case, the heat source is supplied by an electrical power source which is connected to the absorber directly, like a resistive circuit. Considering that the absorber material is copper, a high current is needed and a proper AC-loop is configured with a transformer.

The calibration of the test rig is illustrated in Section 3.1, defining the characteristics of measurement procedure as well as components. In the proposed absorber, the use of reduced dimensions leads us to consider different advantages and disadvantages related to the manufacturing technologies in comparison to the standard PTC. For example, it is not possible to further decrease the diameter of the receiver and also the reflector has to be compact (chord under 500 mm) so the concentration ratio is limited. For this reason, thermal loss per unit aperture area is expected to be higher than in standard PTCs. At the same time, the one side inlet/outlet could help simplify the piping layout and ensures the internal vacuum conditions over time because the glass envelope is sealed itself at the end. However, a high vacuum is needed to keep the thermal loss lower than 25 W/m^2 with a temperature difference between receiver and ambient of around 160 °C. It is also clear that in residential applications a maximum temperature of 180 °C is sufficient for cogeneration (with

ORC) or air cooling (with an absorption chiller). In addition, it is possible to use water as working fluid, which is safe and almost has no environmental impact.

The collected experimental data could allow extrapolating different technical information about the receiver indirectly. In fact, radiation is assumed to be the only heat exchange phenomenon in the vacuum configuration. Since thermal loss, receiver and glass temperature are monitored, the coating emissivity could be derived. Finally, an alternative solution to maintain thermal loss low will be investigated with the same test procedure, filling the gap inside the glass tube with a low-conductivity gas such as krypton. In this configuration higher pressure levels could be applied for the same performance.

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