EXPERIMENTAL DETERMINATION OF PRESSURE LOSS IN SOLAR FLAT PLANE COLLECTORS

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Abstract. The pressure loss determination, in hydraulic circuits, is one of the most important factor at the operation and thermal performance in natural circulation installations (thermosyphon). The values of pressure major losses and minor losses are available at the literature, but not for solar collectors. Therefore, efforts are necessary to define the these values to solar collectors, operate in thermosiphon, in individual or in association.
Some authors propose that the water flow rate is not uniform along the collector association line and ways to determinate the pressure loss. These paper propose one methodology, divided in three stages, to determine it. The first one, it has been developed an experimental assembly to find out the solar collector pressure loss, which has been positioned parallel to the floor and using itself differents mass flows rate one measured unevennes between the columns of water. At the second stage, it have been made several flow rate measurements with the solar hot water system wihch has worked in thermosiphon, with differents tilts and relatives heights. Finally, will be determinate the pressure loss of different associations of collectors and they respective thermal efficiency.

Keywords: *solar domestic hot water, solar collector association, thermosyphon, thermal efficiency, pressure loss.*

1. INTRODUCTION

In Brazil, approximately three millions square meters of solar collector are installed and estimates points that 80% of all systems operate in natural circulation (thermosyphon). Such systems are considered like small-sized installations for domestic application, to attend maximum daily demands of 1,500 (one thousand and five hundred) liters of hot water. However, different configurations are necessary to attend the specific demands of hot water and the operation temperature, which are defined by solar collectors array (series or parallel) that means the profile of hot water daily consumption.

Usually the analytic or experimental approach, which are available in the literature, it were made for the complete system, which included the tank of cold water, the boiler, solar collectors, tabulations and accessories for interconnection of the components, due to the significant influence of the project' s parameters in global efficiency of the solar installation in natural circulation,

For evaluation of each solar collector, an experimental methodology has been proposed by Kudish *et al* (1985) that allows to measurer the water mass flow in the solar collector to intervals of time and for different themosyphon configurations. The advantage of experimental apparatus is the absence of conventional measurement that introduces their own pressure loss into hydraulic circuit as well as external pressures.

The contribution of this research refers to the determination of pressure loss, the K_{efe} coefficient and propose the ideal configuration for solar collectors associations in thermosiphon operation

2. TEORICAL DEVELOPMENT

The natural circulation in solar collectors is a phenomenon that driving force result of temperatures gradient of contained water in the distribution pipes, originated by the solar radiation absorbed by the collector and transferred to the water. The most heated fluid particles and less dense ascend to the top of the collector and therefrom elevate yourself to the boiler at the same time cold water leaves the lower region of the boiler and is dislocated to the entrance of collector, establishing a water flow.

The pressure loss that occurs inside the collector and in the solar installation is calculated by the modified Bernoulli's equation "Eq. (1)":

$$\frac{P_1}{\gamma_1} + \alpha_1 \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma_2} + \alpha_2 \frac{V_2^2}{2g} + Z_2 + \Delta h \qquad (1)$$

where P is the water pressure, V is the mean speed, Z is the relative height and Δh corresponds to the head loss. The parameter α corresponds to kinetic energy correction, which is equals 2 for the laminar pipe flow, Fox *et al.* (2004), which is typical in solar collector (thermosyphon); g and γ represent, respectively, the local acceleration of gravity and the specific weight of the water. This is the product of the specific mass and gravity acceleration, which presents maximum variation of 1.5% at operation temperatures in solar panel, in natural circulation systems. The subscribes 1 and 2 refer to the entrance and to the exit of the collector, respectively.

The head loss is calculated by the sum of the major losses (tubes) and minor losses (accessories) in pipe and in the collector, "Equation (2)":

$$\Delta h = \sum \Delta h_{major\_loss} + \sum \Delta h_{minor\_loss} + \Delta h_{collector\_loss} \qquad (2)$$

The equations mentioned below are used to calculate the total pressure losses are clearly deducted by Fox *et al.* (2004). The pressure loss for fully developed flow in horizontal tube with length L and diameter ϕ, was expressed by the "Equation (3)":

$$\Delta h_{major\_loss} = \frac{32\,\mu\,L\,V}{\rho\,g\,\phi^2} \qquad (3)$$

where ρ and μ correspond to specific mass and viscosity, respectively.

The minor losses could be calculate based on **K** (losses coefficients) that are experimental determinate for each accessories "eq. (4.a)", its available in correlated literature, and K_{efe} for the tested solar collector that is showing in this paper, "Equation (4.b)":

$$\Delta h_{minor\_loss} = \frac{K\,V^2}{2g} \qquad (4.a)$$

$$\Delta h_{collector\_loss} = \frac{K_{efe}\,V^2}{2g} \qquad (4.b)$$

At procedure proposed by Kudish *et al* (1985), the circuit is open to the atmosphere and, therefore, the control volume (reservoir of constant level - solar collector – interconnection tubes) is the atmospheric pressure. However, the specific mass in the exit of the collector is not the same of entrance; therefore the fluid was heated by the solar collector. The initial and final heights are equal, hence the potential energy terms, in the "Equation (1)", are canceled. As the area of the reservoir of constant level is much bigger than the collector exit pipe, its speed in the point 1 is considered null. Applying such simplifications in the "eq. (1)", and "eq. (4.b)", it is able to write the equation of pressure loss for the collector according the "Equation (5)":

$$\Delta h_{collector\_loss} = \frac{P_{atm}}{g} \times \left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right) - \frac{\alpha}{2}\left(\frac{V_2^2}{g}\right) - \sum \Delta h_{major\_loss} - \sum \Delta h_{minor\_loss} \qquad (5)$$

where P_{atm} is the atmospheric pressure and V_2 is the mean velocity of water in the outlet tube.

3. EXPERIMENTAL APARATUS

The experimental workbench utilized at the tests, shown in the "Fig. 1a", it has a manual mechanism that allows modifying the solar collector tilt between 0º to 32º. Next to the workbench was adapted a regulate support that could modify the height, "Fig. 1b", where was installed a constant level reservoir that supplies the collector with cold water. In this reservoir there are three drains, "Fig. 1c", with 200mm, 400mm and 700mm height and a external transparent tube with 900mm that provide a external vision of the internal level of water "Fig. 1d"; his serves to equalize and confirm the internal level of water with the level exit of water. The constant level reservoir is fed by water tank localized next and over to the workbench. There were used the collector tilt angles of 20º, 25º and 30º, owing to be the most useful at solar water heating system in Brazil. At the collector exit, it could be assembly three different pipes (200mm, 400mm and 700mm height) that allow keeping, at the same time, to the level the top of collector with the base of reservoir also the level of the water exit at solar collector with the column of water chosen in the reservoir. For each solar panel tilt, it was used the same height for the collector exit pipe as the drain used of the constant level reservoir - the non used drains were blocked.

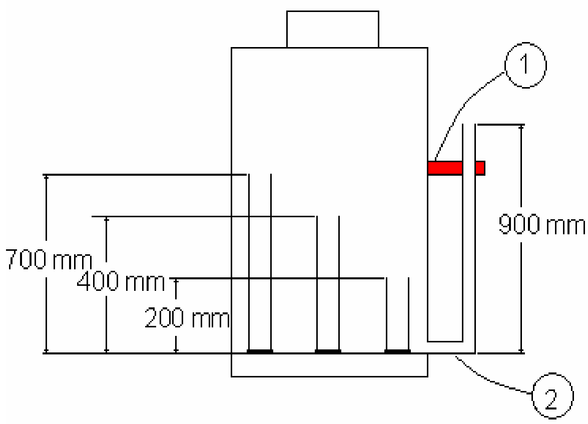
3.1. Instrumentation

The instrumentation used in the tests is described below, according to the ISO 9459-2 standard:
- Thermo-resistance Pt-100: measurement of the ambient temperature (T_{amb}) in the meteorological shelter, entrance water temperature (T_{in}) and exit water temperature (T_{out}) of the collector;
- Piranometer PSP Eppley: measurement of global instantaneous radiation in the collector's plane;
- Multiplexer HP 34970 A: data acquisition for global instantaneous radiation (Rad) and ambient temperature (T_{amb});
- HP BenchLink: software that recorder and storage data of global instantaneous radiation and ambient temperature;

(a) General view of the bench

(b) Detail of the support of regulated height

(c) Drains



(d) Reservoir assembley

Figure 1. Experimental bench

- Workbench for PC for Windows software: data acquisition of T_{in} e T_{out};
- Acquisition board from Omega Engineering: interface between the instrument PT-100 (T_{in} and T_{out}) and the computer;
- Angle measurement (Starret): to gauge the tilt of the solar panel;
- Beaker (Pyrex®): collection and measurement of the water that flowed through the pipes of distribution of the solar collector, taking in its final position;
- Digital chronometer (Technos): register the time of the water volume that goes out of the collector;
- Digital scales (Toledo): measure the mass of the collect water;

- Milimetric ruler made of stainless steel;
- Level (Starret): check levels;
- Acrylic compass (Silva): check the bench orientation;
- Tri-dimension slide caliper that is made of stainless steel (Mitutoyo): check the linear dimension in accessories and tubes of bench.

3.2. Experimental methodology

The experimental planning was carried out for tilts angles of 20°, 25º and 30º regarding the horizontal plan. For each inclination, it was modified the relative height between the exit pipe of solar collector and the base of reservoir for 200mm, 400mm and 700m m and the same time it was used the drain of exactly size.

According to the test standards, the piranometer was positioned in the workbench with the same tilt of the collector. The temperature sensors were thermal insulated and installed at the entrance and at the exit of the collector.

Some daily cares were necessary to guarantee the quality of the experimental data as the verification of the tilt angle, integrity of the thermal insulation and cleaning the collectors. Special attention was required for the correct level between the water exit height of the collector and the water height in the reservoir.

The collectors were maintained covered by a black-out during the night, which was removed at 8:00 AM, for beginning of the tests. The procedure, developed by Kudish *et al* (1985), allows the measurement of the water flow in the collectors, which operating in natural circulation through an open circuit and the radiation created the push, unique present force operating in this system.

This way, every half hour (and several times at minute details intervals to get itself more points to analysis and when it had prevision of clouds), during 1 minute the flow mass of water was collected of exit pipe of water connected to upper gutter of the solar collector; after this it was weighed. They were acquired in the same space of time the measurements of entrance and exit temperatures of the water in the collector, instantaneous global radiation and environment temperature, all treated in his averages in tree minutes (two before more one during the obtainment of flow mass of water therefore it was verified that thermal constant of the collector it was approximately of one minute and fifty-six seconds).

The test was realized until four o' clock in the afternoon in the days with good levels of irradiation. After the last collect of mass of water, it was closed the valve of the tank of water next to bench and also it was covered the collector, to protect it from solar radiation incident that would precede the beginning of the test in next day.

The next step was the treatment of data in electronic spreadsheet; for this it was considered the pressure loss of all pipes and accessories involved as well as the variations of density of water and characteristics of draining at each position of the system. Parallel at project was elaborated in the program E.E.S. (Engineering Equation Solver) a numerical simulation to establish comparisons between the results and the inherents.

The results presented below are for two collectors of a same manufacturer, both tagged by the INMETRO. The difference between them is that the model tested on 2003 has an internal streamer of silicone, as anti-freezing protection, presenting, therefore, higher pressure loss.

4. RESULTS OF THE TESTS

The experimental results are summarized at the graphics in the "Fig. 2" to "Fig. 10" and pressure loss in the "Tab. 1. The results of 2003 are inherents for the collector with anti-freezing protection, and the solar panel used in 2006/2007 there wasn't protection against the water's low temperatures.

Regarding the mass flow in the solar collectors was identified that in the collector with internal streamer of silicon, for the water flows through was required high level of solar irradiation incidence, which is shown on the graphics from "fig. 2A" to "Fig. 10A". Such behavior was justified for greatest value of the pressure loss expected for these collectors, fact explained by the expressively restriction area path to the mass flow.

The "Fig. B" shows up the influence of the difference of temperature in the ooze mass flow by thermosyphon. For the same temperature difference the flow produced in the common collector is always upper then collector with silicon. A comparison between the "Fig. 2.B", to "Fig. 10.B" shows that, for collectors with 20º tilt angle, as much as higher the unevenness between the exit of the collector and base the reservoir, smaller is difference of temperature necessary to ooze flow either initiated. For example: for 20º and 200mm and 20º and 700mm, that difference of temperature decreases from 313 K (40º C) to 301 K (28º C), respectively. For the same unevenness (700mm) the "Fig. 4.b" and "Fig. 7.b", show up the influence of the tilt of the collectors. In that case, the increase of the inclination from 20º to 25º reduces the difference of temperature demanded from 301 K (28º C) to 293K (20º C). The graphics "C" and "D" correlate the irradiation and the mass flow with pressure loss respectively. The configuration 30º with 700mm one showed the best of all due to present the minor pressure loss at conditions of test.

Finally was observed, in the realized tests, irregularities in temperatures and flow mass in the higher and low bands of irradiation, whose reason will be investigate in future tests and different configurations.

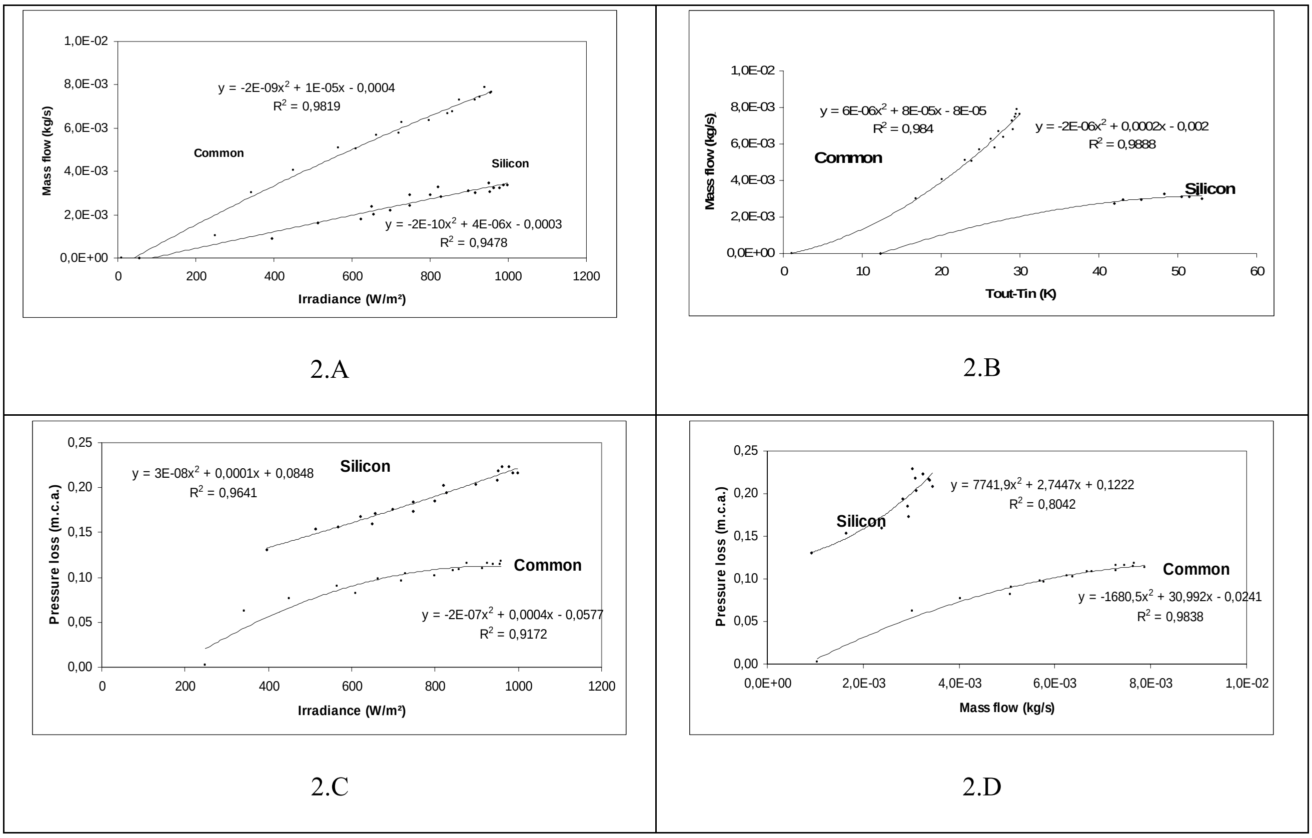


Figure 2. Dynamic behavior of solar collector of 20º tilt and 0.20 m of unevenness.

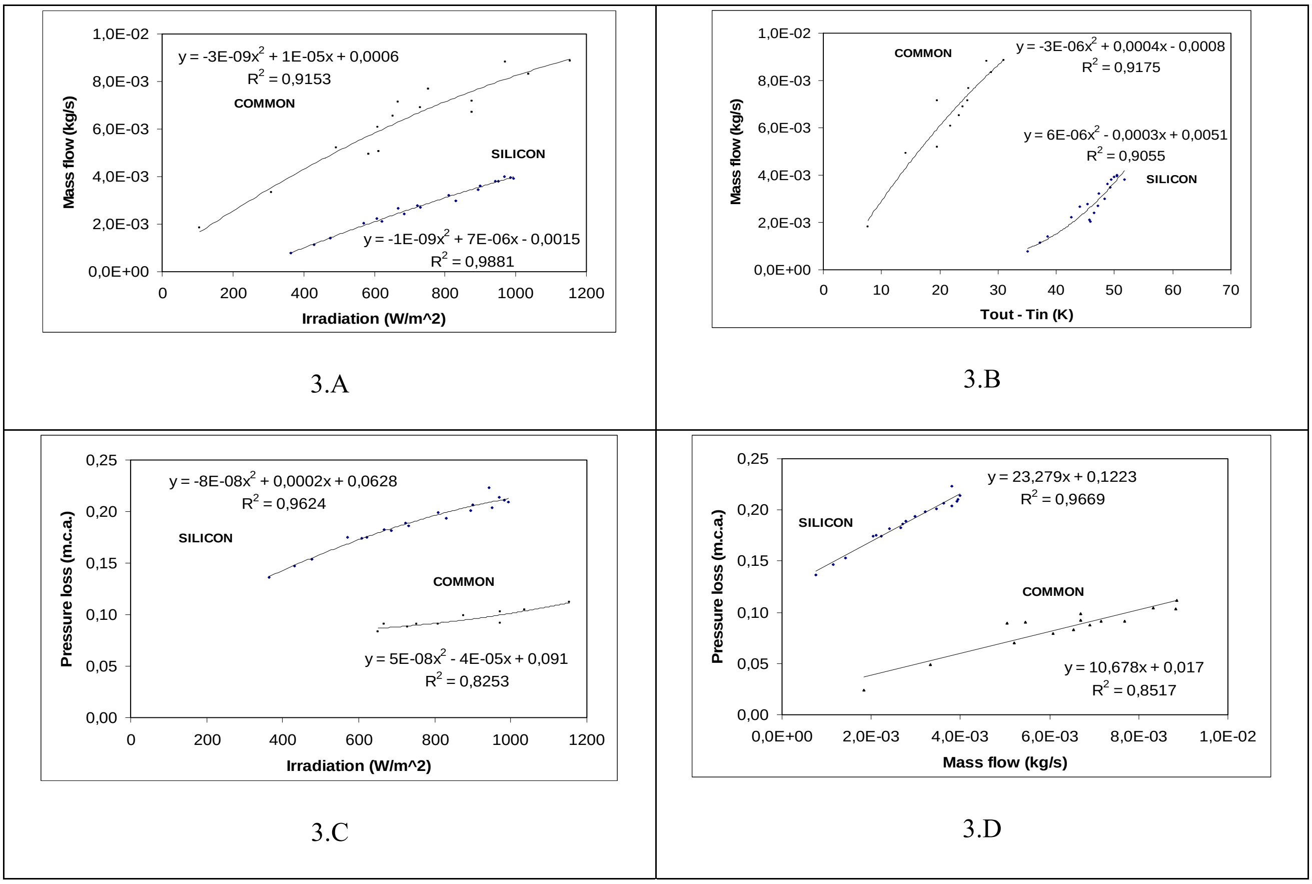


Figure 3. Dynamic behavior of solar collector of 20º tilt and 0.40 m of unevenness.

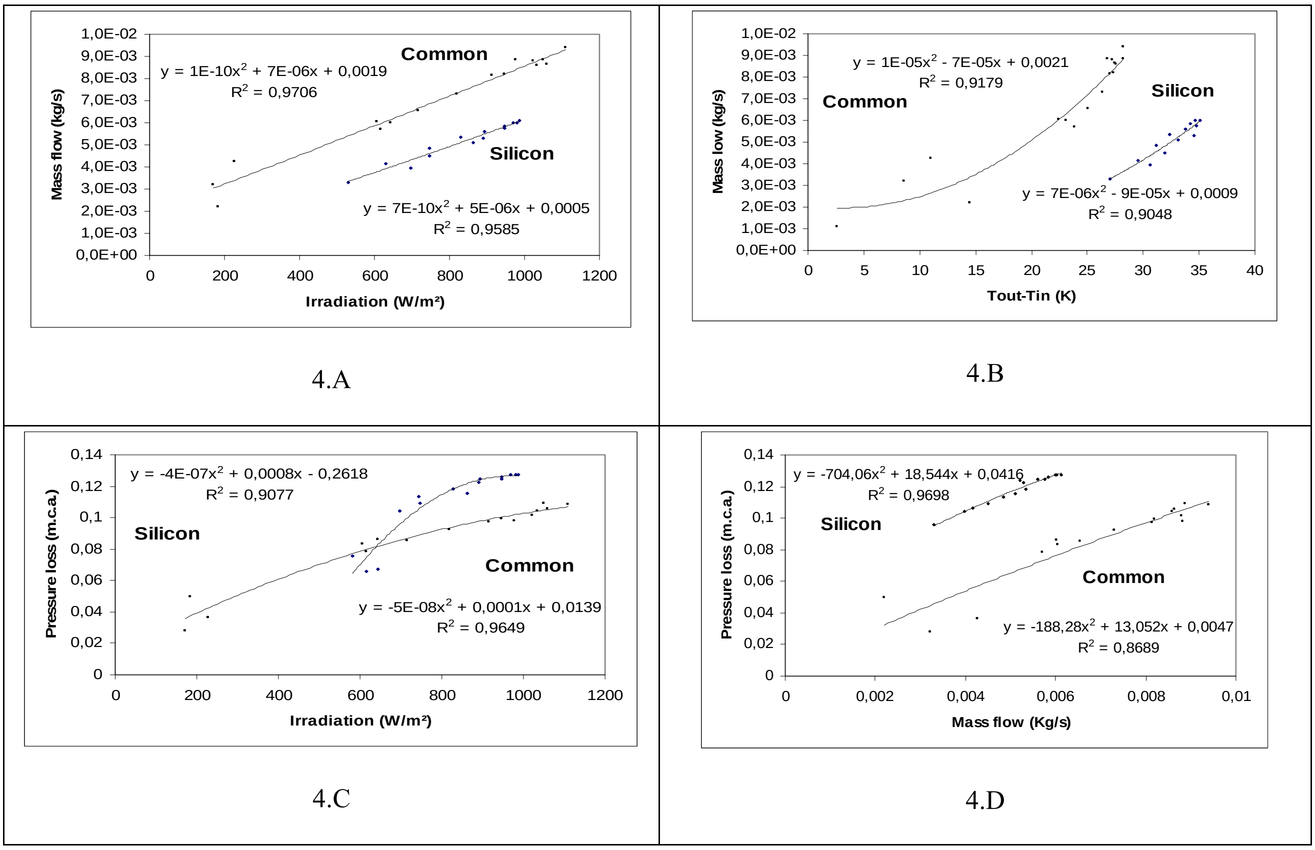


Figure 4. Dynamic behavior of solar collector of 20º tilt and 0.70 m of unevenness.

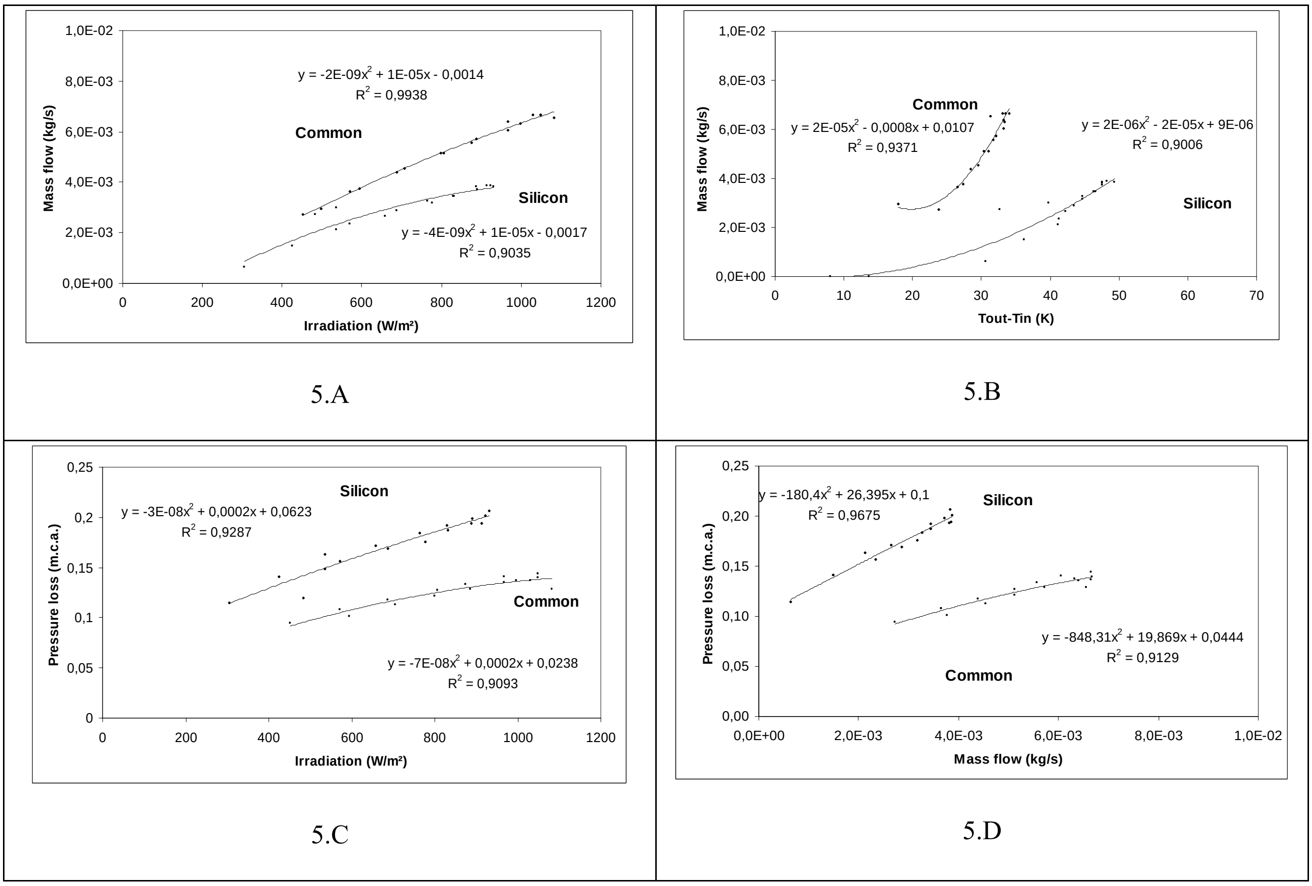


Figure 5. Dynamic behavior of solar collector of 25º tilt and 0.20 m of unevenness.

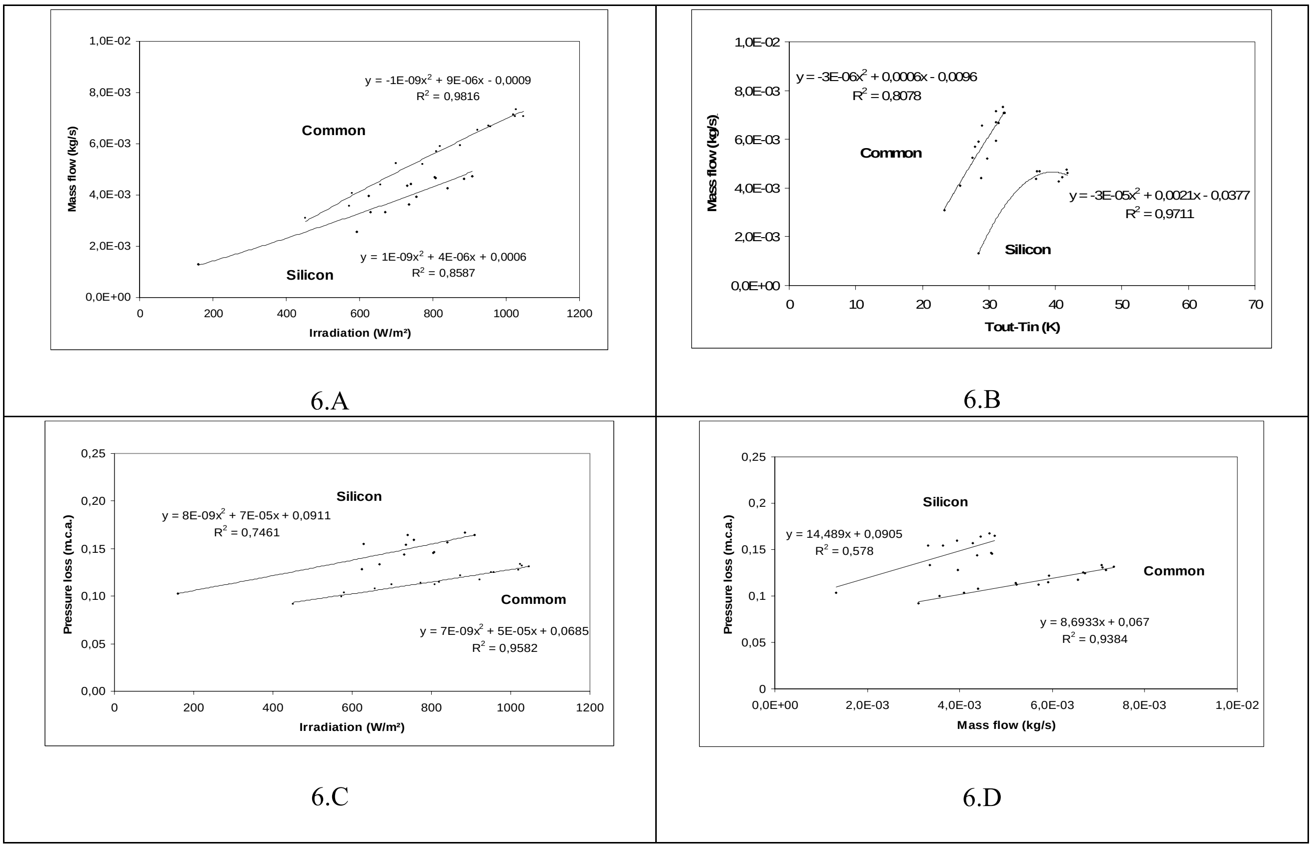


Figure 6. Dynamic behavior of solar collector of 25º tilt and 0.40 m of unevenness.

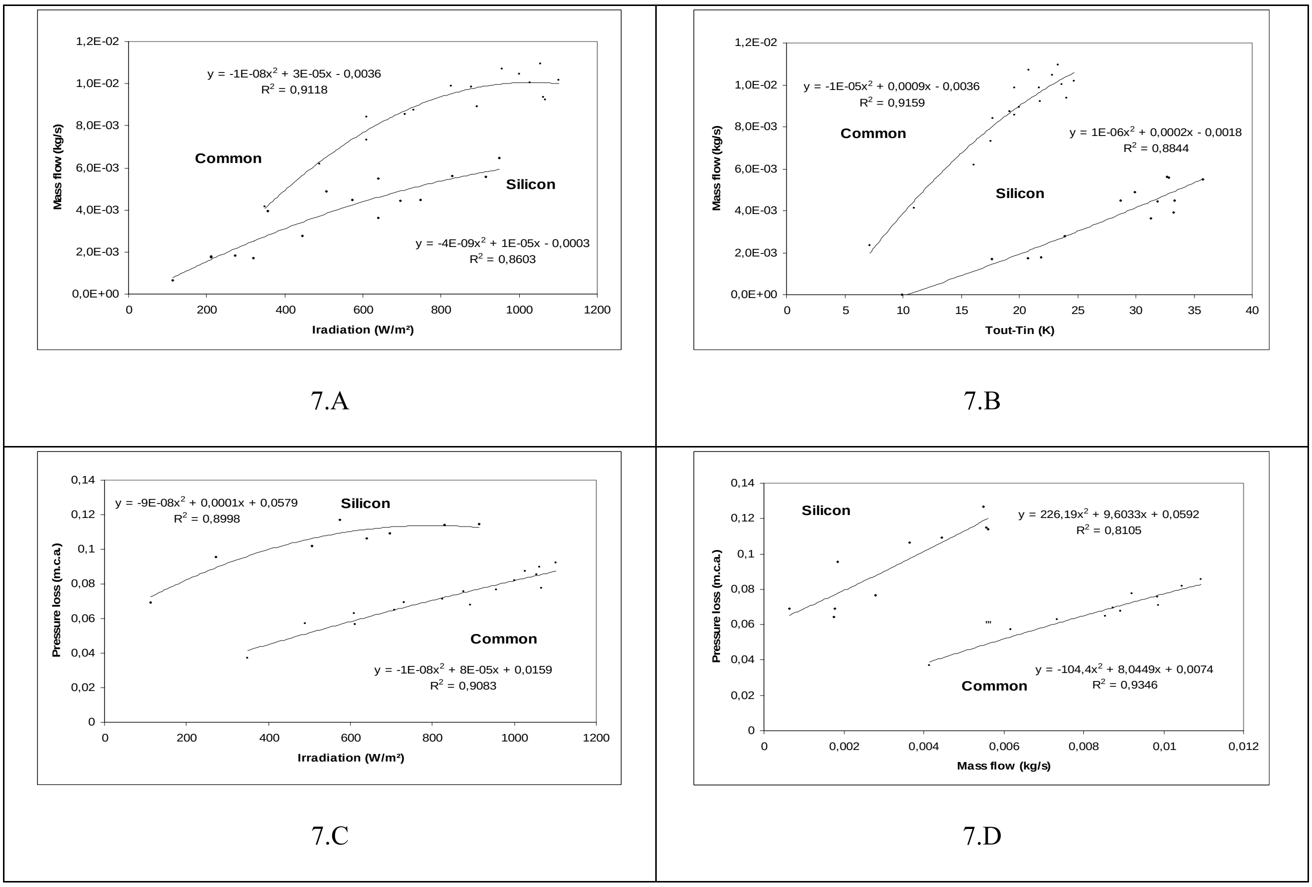


Figure 7. Dynamic behavior of solar collector of 25º tilt and 0.70 m of unevenness.

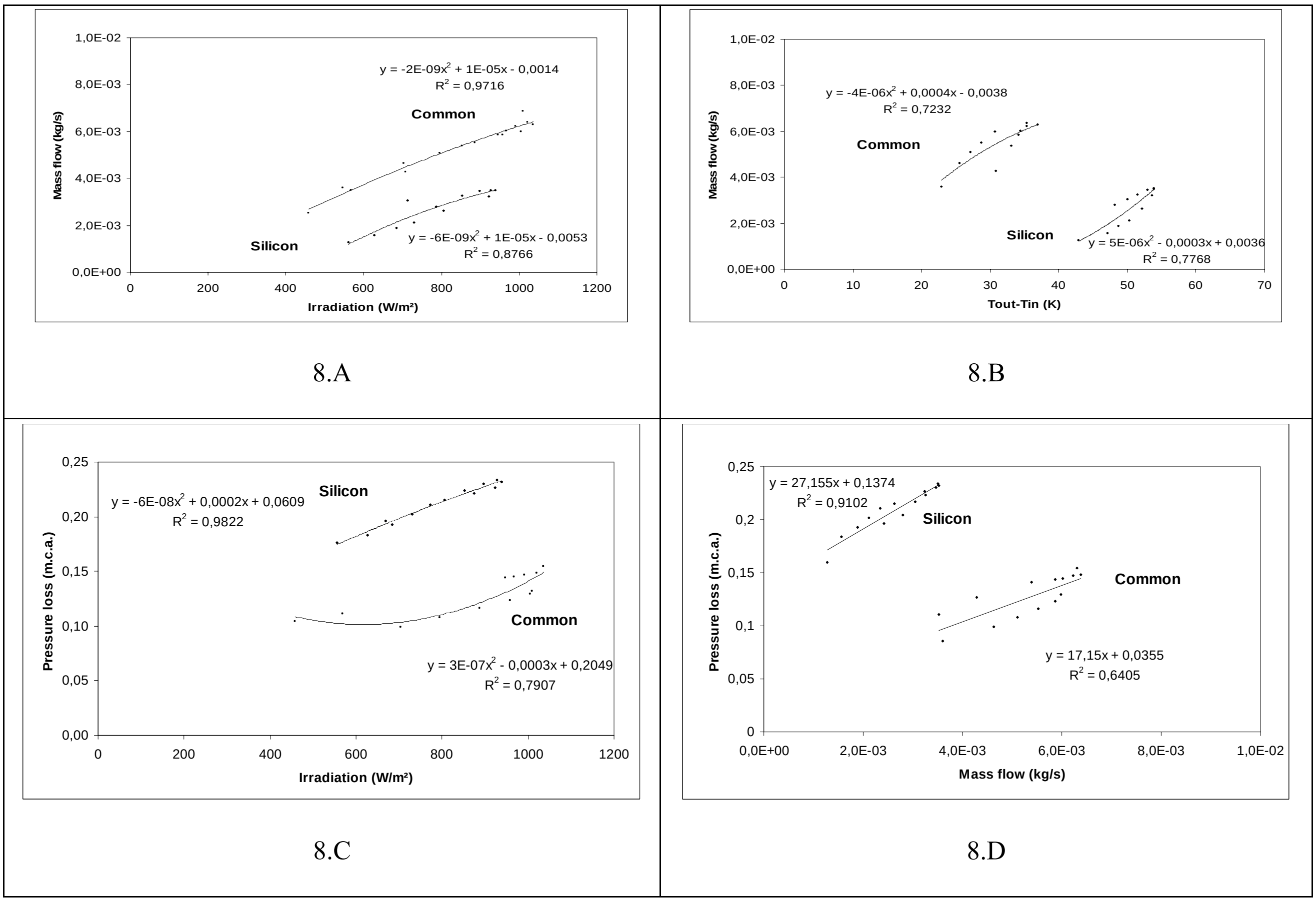


Figure 8. Dynamic behavior of solar collector of 30º tilt and 0.20 m of unevenness.

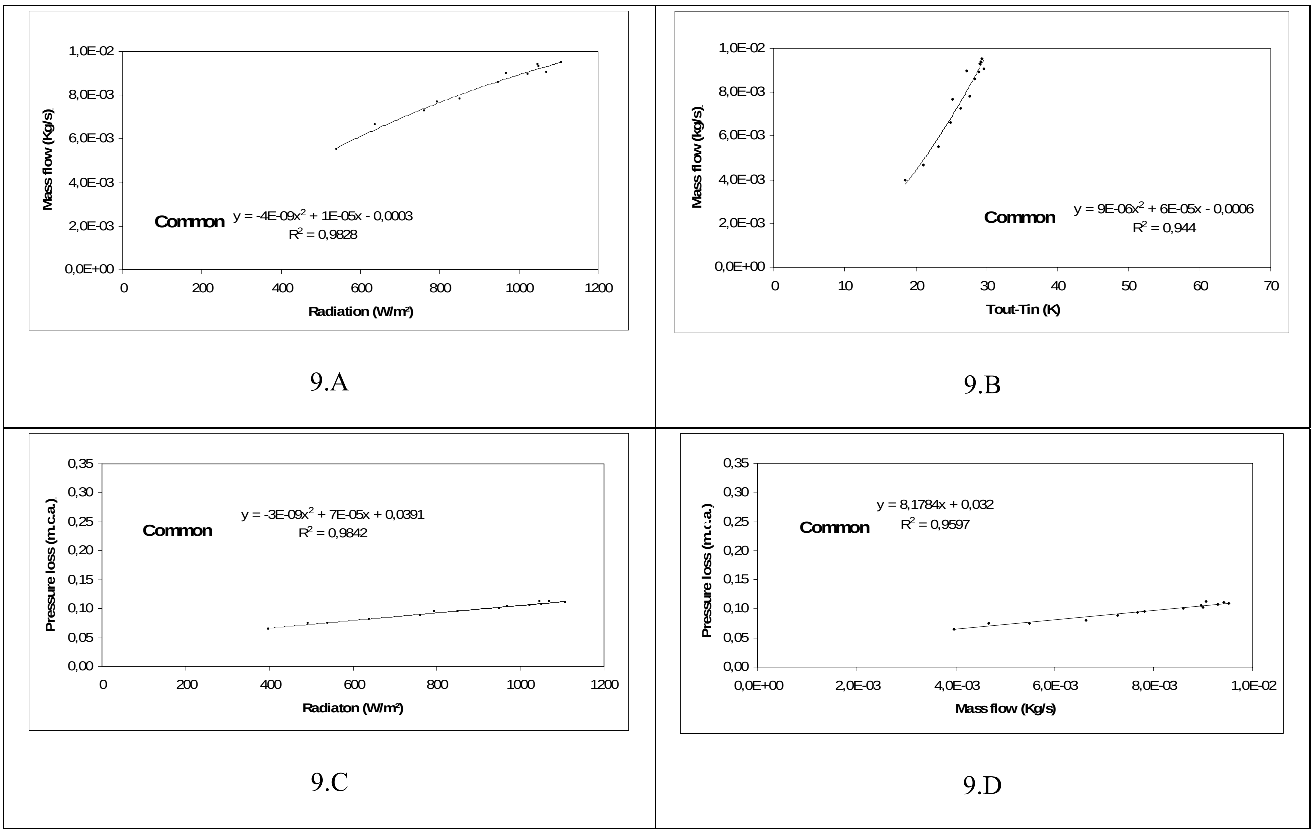


Figure 9. Dynamic behavior of solar collector of 30º tilt and 0.40 m of unevenness.

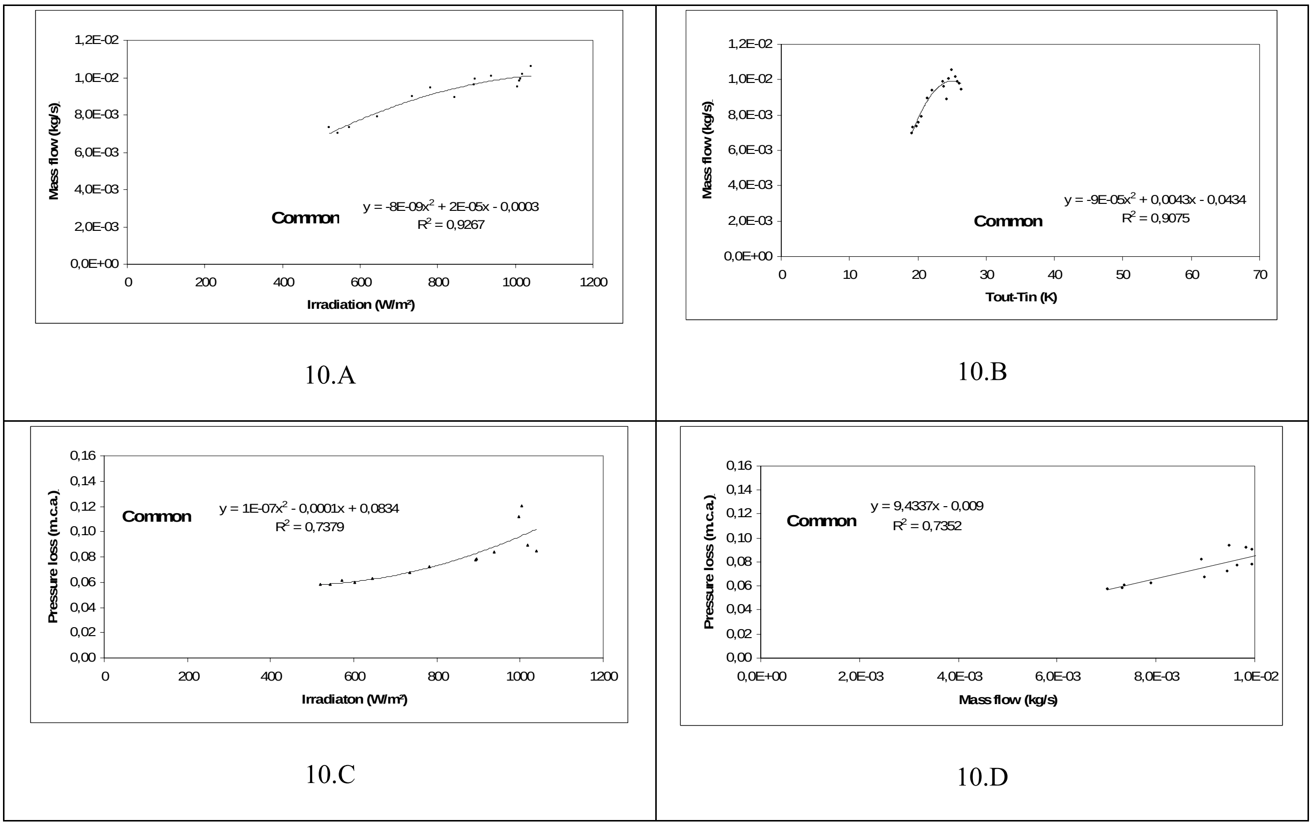


Figure 10. Dynamic behavior of solar collector of 30º tilt and 0.70 m of unevenness.

Configuration (tilt x unevenness)	**Pressure loss(1) (m.c.a.)**	**Pressure loss(2) (m.c.a.)**
20º x 0.20 m	0.1087 $^{+}$- 0.0059	0.1991 $^{+}$- 0.0186
20º x 0.40 m	0.0928 $^{+}$- 0.0095	0.2015 $^{+}$- 0.0097
20º x 0.70 m	0.0988 $^{+}$- 0.0065	0.1168 $^{+}$- 0.0104
25º x 0.20 m	0.1311 $^{+}$- 0.0077	0.1885 $^{+}$- 0.0101
25º x 0.40 m	0.1222 $^{+}$- 0.0068	0.1549 $^{+}$- 0.0075
25º x 0.70 m	0.0783 $^{+}$- 0.0075	0.1074 $^{+}$- 0.0053
30º x 0.20 m	0.1318 $^{+}$- 0.0136	0.2159 $^{+}$- 0.0112
30º x 0.40 m	0.1045 $^{+}$- 0.0052	To be confirmed
30º x 0.70 m	0.0804 $^{+}$- 0.0078	To be confirmed

(1): **Common collector** (2): **Collector with silicon**

Table 1. Loss coefficients to the solar collectors (common and silicon streamer panels).

5. CONCLUSIONS

The experimental procedure proposed by Kudish *et al* (1985) and implemented in this study, it allows to evaluate the operational characteristics of flat plane solar collectors, which is operating in natural circulation in function of solar water heating installation parameters and irradiance incidence conditions at each locality. Its appropriate to comment of this experiment to displaced extremely sensitive how much at unevennesses, demanding delayed cares to reach itself perfect levellings.

The results obtained comply with the values expected from the theoretical concepts involved. On the basis of these results is able to select the optimized configuration for the positioning of the solar collector and boiler.

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7. NOMENCLATURE

P_1, P_2	local atmospheric pressure (in,out)	Pa
γ_1, γ_2	specify weight	$kg.m^{-2}.T^{-2}$
α_1, α_2	kinetics energy coefficient	
V_1 , V_2	mean speed of the fluid (in, out)	$m.s^{-1}$
g	acceleration of gravity	$m.s^{-2}$
Z_1, Z_2	height	m
Δh	head loss	m H_2O
Δh_{major_loss}	major loss	m H_2O
Δh_{minor_loss}	minor loss	m H_2O
$\Delta h_{collector\_loss}$	collector's minor loss	m H_2O
μ	viscosity	$kg.m^{-1}.s^{-1}$
L	length	m
V	mean speed of water	$m.s^{-1}$
$V_{collector}$	mean speed of water in the collector	$m.s^{-1}$
ρ	specific mass	$kg.m^{-3}$
ϕ	diameter	m
K	loss coefficient	
K_{efe}	collector's loss coefficient	

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