FIELD TEST OF WATER-STEAM SEPARATORS FOR THE DSG PROCESS

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Abstract

Direct steam generation (DSG) in parabolic trough collectors is a promising option for improving mature SEGS type parabolic trough technology for solar thermal power plant application. The European DISS and INDITEP projects have proven the feasibility of the DSG process in parabolic trough collectors under real solar conditions at the life size DISS test facility at the Plataforma Solar de Almería (PSA) [1]. These projects have also shown that the recirculation mode is the preferred operation mode for DSG collector fields for near term applications. The water-steam separator is a key component of collector fields operated in recirculation mode. Both compact water-steam separators for every single row or huge separation drums for the whole collector field are conceivable. Small compact water-steam separators offer the advantage of a lower inertia, thus reducing the time for start-up and lower investment. Within INDITEP and the German R&D project SOLDI compact water-steam separators have been developed, manufactured and tested by DLR and Siemens, with its subcontractor Framatome ANP. Prototypes of a cyclone and a baffle separator have been implemented into the DISS test facility. More than 200 tests have been performed to investigate the separation efficiency, the pressure loss and the performance under transient conditions.

Keywords: water-steam separator, direct steam generation, cyclone separator, baffle separator

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Introduction

In the European R&D project INDITEP, a Spanish-German consortium has taken the last step in the demonstration of DSG technology in MW scale. The main work package was the detailed engineering of a demonstration plant with a net power of 5 MW. In a second work package key components of a DSG collector field such as high pressure ball joints or compact water-steam separators have been investigated.

Siemens, with its subcontractor Framatome, has developed two different compact small cyclone separators. These cyclones were designed to be implemented into the DISS test facility at the PSA. Accordingly, they had to withstand the design parameters of the DISS test facility ($p = 100$ bar, $T = 400°\mathrm{C}$). More than 150 tests have been performed to investigate their performance under steady-state and transient conditions. In parallel, DLR has developed a baffle separator for comparison. The design and construction of the baffle separator was funded by the German Federal Ministry for the Environment (BMU).

In the first sections of this paper the basics of the investigated separators will be presented. After explaining the test set-up and the chosen analysis procedure the main results will than be presented and discussed.

Cyclone Separator

Centrifugal forces are responsible for the phase separation in cyclones. A two-phase mixture enters tangentially into the cyclone causing a spiral motion of the gas phase. The axial flow is directed downwards in the outer region and upwards in the core region with the cleaned gas leaving the cyclone through the vortex finder. The particles in the stream are centrifuged to the wall where they move downwards into a collecting chamber. Depending on the type of particles to be separated, different geometrical designs of cyclonic separators are used. For the separation of liquids, no conical section in the lower part of the cyclone is necessary. Instead, a simple cylindrical cyclone is used, which can be divided into an upper section where separation takes place and a lower section where the liquid is collected. This design has the advantage of guaranteeing a well-defined flow situation in the upper part. In combination with a vortex breaker at the water outlet a sufficiently high liquid level in the lower part avoids the problem of gas being suctioned into the liquid outlet. Furthermore, only a flat liquid surface allows the measurement of the liquid level, which is necessary for the control of the liquid discharge. In the present investigation, cylindrical cyclones of two different body diameters are used. The first cyclone has an inner diameter of 76.1 mm (Cyclone 1). The second cyclone has an inner diameter of 88.9 mm (Cyclone 2).

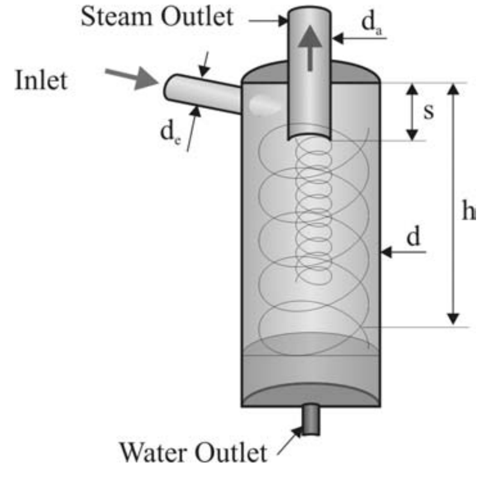

Figure 1: Schematic diagram of a cyclone separator (Not to scale)

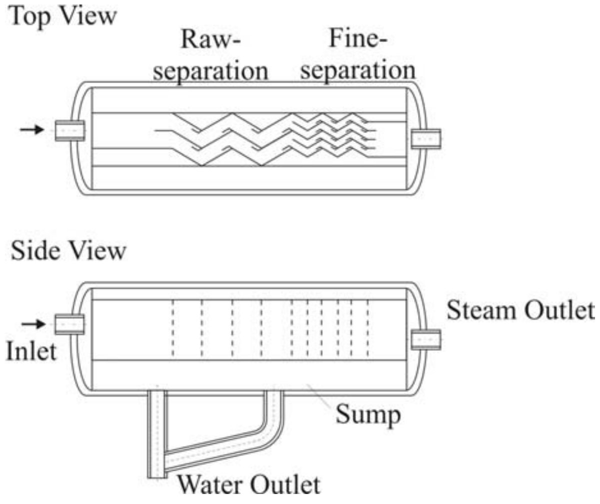

Figure 2: Schematic diagram of a baffle separator.

Baffle Separator

Baffle separators are a common device especially designed for droplet elimination from gas streams. Typical applications are air dryers in cooling devices and air cleaners for industrial exhaust streams with cut sizes in the range of 5 to 30 microns. In principle two different configurations are possible. First the gas stream can be directed horizontally through the wave-plate package and separated particles move downwards on the walls or can be collected in drainage channels. Second, the gas stream can be vertically directed upwards causing small droplets to be separated on the wave-plates. There they form a film flowing downwards against the gas stream. Larger droplets created by film break-up are now able to overcome the drag in the gas stream and fall into a sump. For the present investigation, a design with horizontal gas stream is used, see figure 2.

Test Set-Up and Procedure

The DISS test facility has a total length of 700 m. The compact water steam separators presented in this paper are installed 100 m in front of the end of the collector loop. Accordingly, the first 600 m are used as an evaporation section and the last 100 m as a superheating section (s. Fig. 3). The water-steam mixture from the evaporation section enters the separator, where the separated steam is than fed to the superheating section. The water outlet of the separator is connected to a vessel with a volume of 4 m^3 and drained by gravity. Under steady state conditions no water remains in the separator. The water in the vessel is finally re-circulated to the inlet of the collector loop.

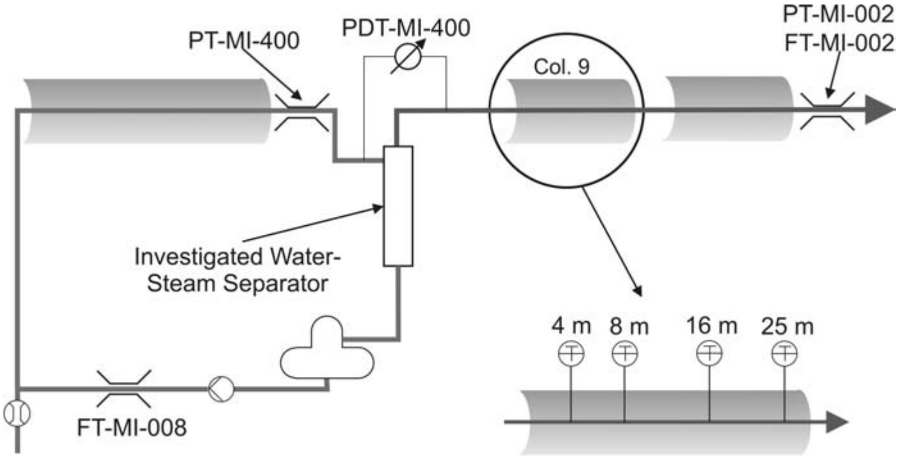

Figure 3: Schematic Setup of the DISS test facility with the used measuring points.

For the assessment of the different separators two main parameters characterize the steady-state performance; the separation efficiency and the pressure loss caused by the separator. The pressure loss is measured by a differential pressure sensor that measures the pressure loss between the separator inlet and its steam outlet. In addition, the influence of swirl breakers at the steam outlet of the separator is investigated by differential pressure sensors over the collectors within the superheating section.

The separation efficiency is determined by a heat balance on the first collector of the superheating section, collector 9. Collector 9, the so called special test collector, is chosen since it is equipped with the most thermocouples along its length allowing for the most reliable thermal analyses (s. figure 3). Collector 9 has a thermocouple at the collector inlet measuring the fluid temperature and several thermocouples along the collector length measuring the wall temperature. For the thermal analyses the so called *A*-thermocouples, located in opposition to the irradiated region of the absorber tube are used.

The thermocouples along the superheating section are used to determine the position where the superheating begins. This is the position where the temperature exceeds the saturation temperature of the compressed water. This position is displayed in figure 4 for two different steady-state tests. Once this point is identified, a detailed energy balance is used to determine the amount of water torn out into the superheating section and thus the separation efficiency of the separator.

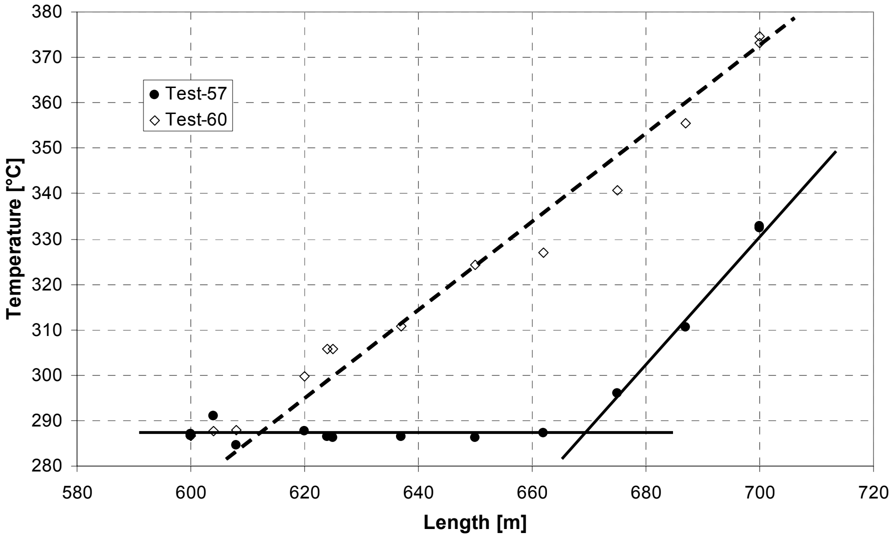

Figure 4: Measured temperatures along the superheating section for two different steady-state tests (collectors 9 to 11 from l = 600…700 m).

Error Analysis

The pressure loss of the separator is measured directly by pressure drop transmitters mounted at the positions of interest. The measurement error can then be expressed by the accuracy of the sensors. The absolute accuracy of the pressure drop transmitter used is 0.07 bar.

The separation efficiency is not measured directly. As described above it depends on several measured values and calculated quantities. Accordingly, the accuracy of the determined efficiencies depends on numerous factors such as the accuracy of sensors used, faulty determination of steam properties and un-precise consideration of heat losses. The accuracy of the sensors used for the calculation is listed in Table 1.

All Temperatures are measured with an accuracy of 1 K. The law of error propagation is applied to the evaluation procedure used. As displayed in figure 5, the accuracy depends strongly on the inlet steam quality. The higher the steam quality the higher the error. An increasing steam quality means a decreased water content of the two phase flow at the separator inlet. If this water content decreases more and more it will be more difficult to detect the accordingly lower water mass flux passing through the separator. Although the measurement error is very high for steam qualities higher than 90 %, the evaluation procedure used is appropriate to assess different separators for inlet steam qualities lower than 90 %. Since the design inlet steam quality for the planned INDITEP power plant is 75 %, the measured results are useful for a first assessment of the investigated separator options.

	Sensor	Accuracy	Unit
Mass Flux	FT-MI-002	0.04	kg/s
	FT-MI-008	0.03	kg/s
Pressure	PT-MI-002	0.7	bar
	PT-MI-400	0.7	bar
Pressure Drop	PDT-MI-400	0.07	bar

Table 1: Absolute accuracy of the sensors used (For further information on the sensor position s. figure 3).

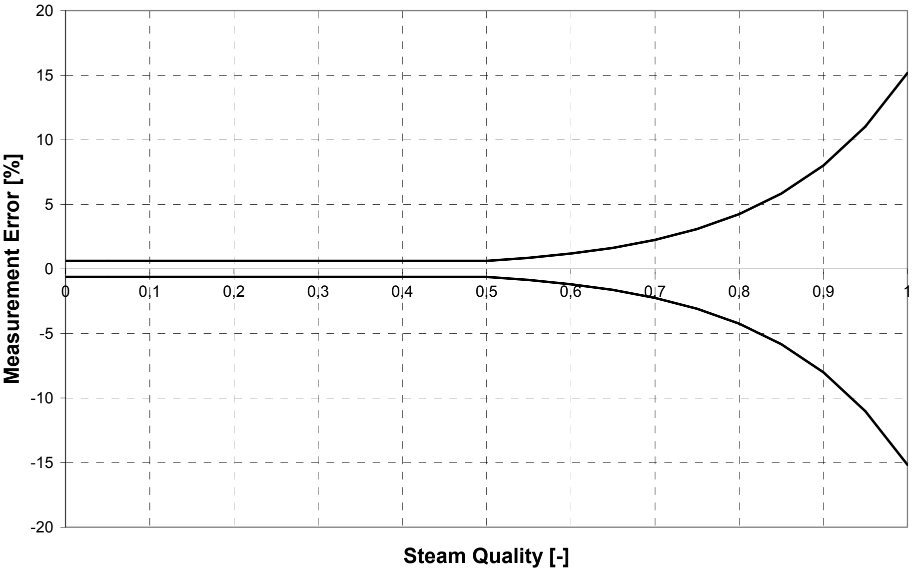

Figure 5: Measurements accuracy for several measured separation efficiencies as a function of the inlet steam quality.

Results

Pressure Loss

The pressure loss coefficient ζ of a separator is expressed by equation (1).

$$\zeta = \frac{\Delta p}{\frac{\rho}{2} w^2} \tag{1}$$

Where Δp is the measured pressure drop, ρ the fluid density and w the velocity. In both cases the velocity is calculated with the cross section of the absorber pipe (50 mm). For separators the pressure loss coefficient is not constant but depends on the liquid load and thus of the steam quality at the separator inlet. Figure 6 displays the pressure loss coefficient for the investigated separators as a function of the inlet steam quality. According to figure 6 the pressure loss coefficient increases with an increasing amount of water at the separator inlet. With higher steam qualities the pressure loss converges to the value for the pure steam flow expressed by a steam quality of one.

Another important result is that the pressure loss of the cyclones is more than five times higher than that of the baffle separator. This is mainly caused by the perpendicular redirection of steam flow in the cyclones causing a large change in momentum. Figure 6 also shows that the pressure loss coefficient of the cyclones is very sensitive to their inner diameter. The pressure loss of cyclone 1 (inner diameter 76.1 mm) is roughly twice as high as that of cyclone 2 (inner diameter 88.9 mm). Therefore, a further increase of the cyclones inner diameter could reduce its pressure loss significantly. However, increasing the inner diameter more and more would lead to cyclones that are no longer *compact*. According to the performed investigations, baffle separators tend to lower pressure losses as cyclones. Finally, it has to be stated that the parasitic power consumption of the collector field caused by the pressure loss (0…2 bar for the operation range of a DSG collector loop) is negligible compared to the thermal power of the collector field [2].

Separation Efficiency

The efficiency of a separator η_{sep} is defined by equation (2) as the ratio of the separated liquid mass flux to the total liquid mass flux at the separator inlet.

$$\eta_{sep} = \frac{\dot{m}_{L,sep}}{\dot{m}_L} \tag{2}$$

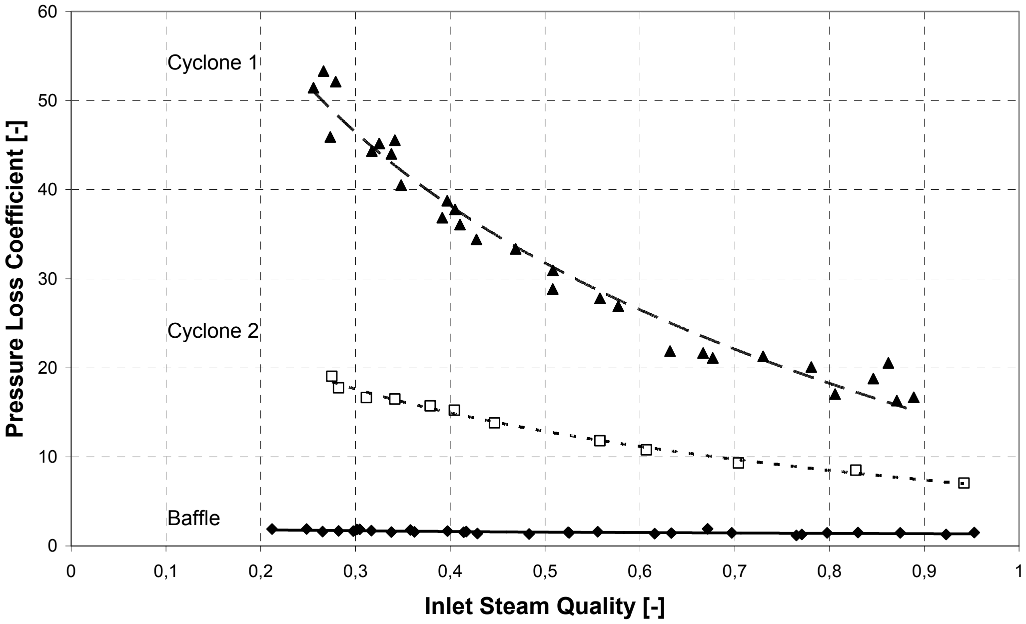

Figure 6: Pressure loss coefficient for the investigated separators as a function of the inlet steam quality measured at 70 bar.

As a first step, the influence of the operation pressure on the separation efficiency is investigated. Figure 7 displays the results for the baffle separator. According to figure 7 the operation pressure has no influence on the separation efficiency. The same result was achieved for the cyclones. Furthermore, it was observed that the inner diameter of the cyclones has no influence on the measured separation efficiency.

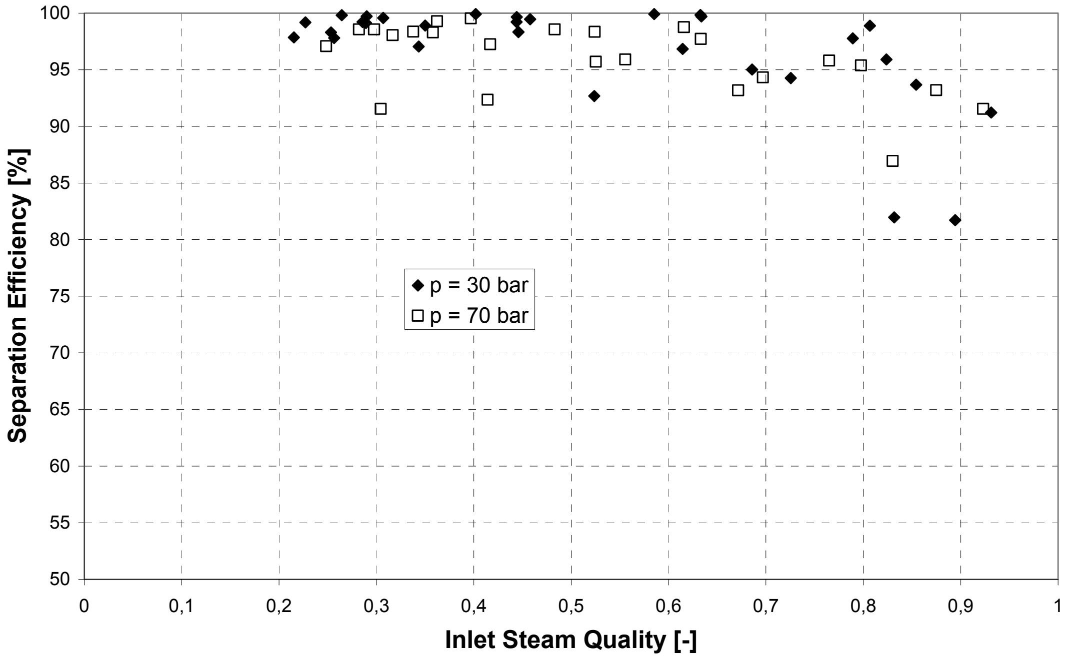

Figure 7: Measured separation efficiency of the baffle separator for different operation pressures.

The separation efficiencies measured for the cyclones and the baffle separator are compared in figure 8. According to figure 8, there is no distinct difference between the measured efficiencies. For steam qualities higher than 0.6, the difference is smaller than the measurement error (s. figure 5). For lower steam qualities, the baffle separator tends to higher separation efficiencies. This statement is supported by figure 9 where the position of the beginning of the superheating is plotted as a function of the steam quality.

Again, the baffle separator tends to shorter evaporation lengths for lower steam qualities. The most interesting conclusion that can be drawn from figure 9 is that both separators have a threshold value of the inlet steam quality. Above this threshold, the measured evaporation length is nearly constant. This threshold value corresponds to the steam quality in figure 8 where the separation efficiency starts to decrease significantly at approx. 0,7. If the steam quality at the steam outlet of the separator is plotted as a function of the steam quality (not presented in this paper) it turns out that this steam quality increases slightly until the observed threshold and then tends to remain constant at a value higher than 95 %. Accordingly, the cyclones especially seem to have a minimum water load that causes an overflow of the separator.

From figure 9 it can be deduced that the separators are operated best at an inlet steam quality between 0,7 and 0,8. In this operation range the evaporation length within the superheating section is no longer decreasing and the separation efficiency is still higher. Furthermore this operation range guarantees a sufficient safety margin against dry-out at the separator inlet (end of evaporation section) under transient conditions.

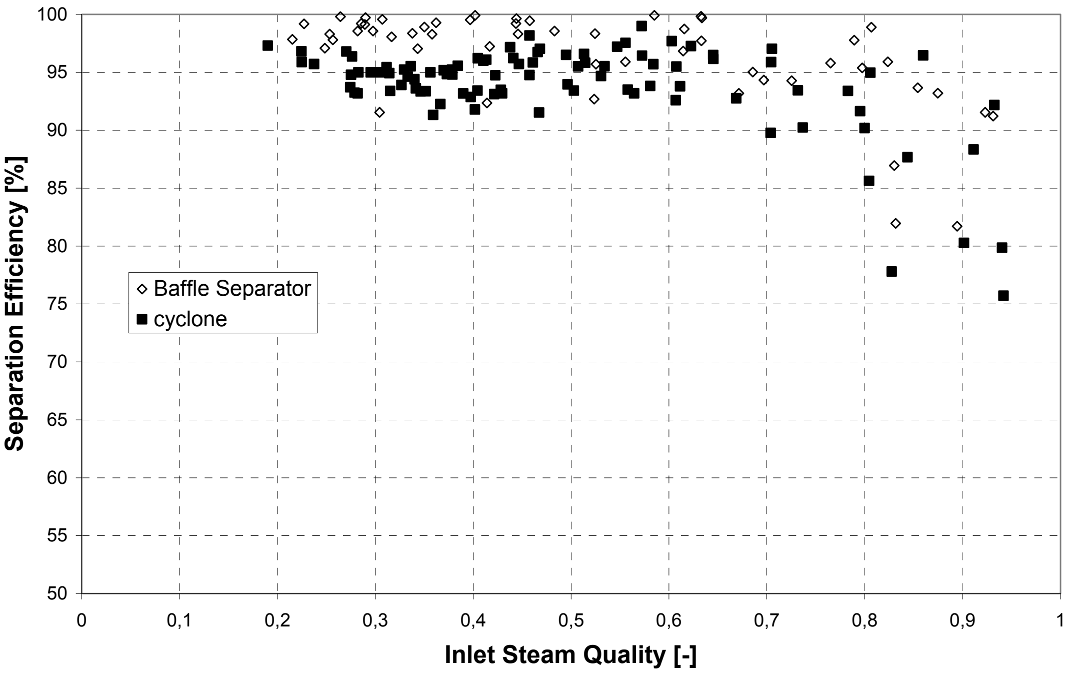

Figure 8: Measured separation efficiency of the baffle and the cyclone separator.

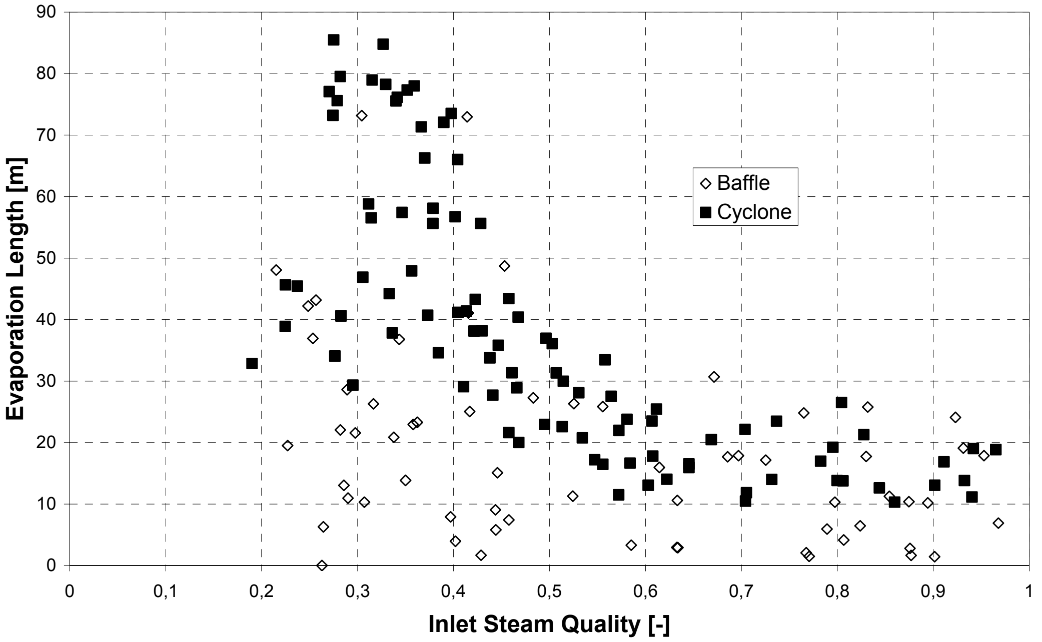

Figure 9: Measured evaporation length within the superheating section of the baffle and the cyclone separator.

Conclusion

A baffle separator and two cyclone separators with different inner diameters have been designed, manufactured and tested under real solar conditions at the DISS test facility at the Plataforma Solar de Almería (PSA) in Spain. Both separator systems have been assessed regarding their pressure loss characteristics and their separation efficiency. It was found that the investigated baffle separator has a lower pressure loss coefficient than the cyclones. The pressure loss coefficient depends on the steam quality at the separator inlet but not on the operation pressure. In case of the cyclones, the pressure loss coefficient is very sensitive to the inner diameter of the cyclones.

The characteristic of the separation efficiency of both separator types is similar. Both separator types have an excellent separation efficiency (> 95 %) for lower inlet steam qualities. For both separator types the efficiency decreases with increasing inlet steam quality but their performance is still satisfying. The operation pressure and the inner diameter of the cyclones have no significant influence on the separation efficiency. The observed deviation between the investigated separators is within the measurement accuracy of the assessment procedure used.

The investigation presented in this paper has shown that compact water-steam separators are available that offer a good system performance under real DSG conditions. The ideal operation range for both separators is an inlet steam quality of 0.7 to 0.8.

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References

[1] Zarza E., Valenzuela L., León J., Hennecke K., Eck M., Weyers H.-D., Eickhoff M.: *Direct Steam Generation in Parabolic Troughs Final Results and Conclusions of the DISS Project*, Energy, Vol. 29 (2004) pp. 635-644

[2] Eck M., Zarza E.: *Assessment of Operation Modes for Direct Solar Steam Generation in Parabolic Troughs*, 11th International Symposium on Solar Thermal Concentrating Technologies, Zurich (2002) p. 591-598