

# Pressure drops for direct steam generation in line-focus solar thermal systems

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*New two-phase flow modelling undertaken for the Compact Linear Fresnel Reflector solar steam generator gives significantly improved agreement with published experimental results for a comparable system. Modelling is extended to include losses in connecting pipe-work, bends and valves, and updated pressure drop and heat transfer correlations are employed. The modelling shows good agreement with the experimental results, to the extent possible with the available data.*

## 1. INTRODUCTION

Direct Steam Generation (DSG) is increasingly the approach taken for new large-scale solar thermal energy projects. Compared to earlier systems, most notably the SEGS system in California, which used synthetic heat transfer oil to convey heat from the focus of the solar collector, and then generate steam outside the collector in a large heat exchanger, DSG systems instead aim to generate steam directly within the collector. This eliminates the heat exchanger and allows higher temperatures to be achieved due to operational limits associated with the chemical breakdown of the heat transfer oil. With higher temperature comes the promise of higher cycle efficiencies. DSG also offers the possibility of lower pumping costs, due to lower pressure drops for water and steam, compared with oil, and improved heat transfer due to the forced convection boiling mode (Muller 1991).

The Compact Linear Fresnel Reflector (CLFR) is a concentrating solar thermal energy concept developed at the University of Sydney and University of New South Wales since the early 1990s (Mills and Morrison 2000), now in the commercialization phase at the Liddell power station in the Hunter Valley, New South Wales.

The CLFR is a linear concentrator with a modular design concept. As a linear Fresnel reflector, it uses a bank of parallel mirror rows (each row 310 m long) to focus solar radiation onto a long absorber positioned above the mirrors. The absorber consists of a number of closely-packed pipes mounted at the top of a downward-facing trapezoidal cavity. The cavity is insulated above and covered with a glass window on the bottom. A novel aspect of the CLFR concept is its compact modular format. A full-scale CLFR is comprised of many parallel absorbers, and the mirror rows are configured such that at locations mid-way between absorbers, adjacent mirrors point at alternative absorbers. This allows close packing of mirrors without the introduction of the shading losses that would normally result.

The aim of the present work is demonstrate a reliable fluid flow model for use in modelling of the CLFR absorber by validating it against published results for a similar system. We will computationally model the experimental cases described by Rheinlander (2002) and compare with the experimental results published there.

## 2. RELATED WORK

Early direct steam generation prototypes include two central tower projects: a solar-powered enhanced oil recovery project called STEOR in the early 1980s (Romero 2002), and a solar tower project the Wiezmann Institute in Israel in the early 1990s (Epstein 1991). These projects used central-tower receivers, so although these projects were aimed at achieving the benefits of DSG, they do not offer results applicable to DSG in long horizontal pipes as required for the current work with a line-focus collector.

Following the experience of Luz International with the oil-based SEGS systems in California, efforts were underway at Luz to investigate direct steam generation (Zarza 1997). This work was subsequently taken on by CIEMAT (Spain) and DLR (Germany), two European government-based research groups. The DISS project at the Plataforma Solar de Almeria was the eventual result, which resulted in a 480 m prototype collector using Luz parabolic troughs equipped with a 50 mm ID evacuated tube DSG receiver. Experimental results were gathered and reported by Rheinlander (2002). Rheinlander then performed computational modelling using the two-phase pressure drop correlation of Friedel as well as heat loss modelling due to Ajona (Rheinlander 2006) and was able to reproduce experimental results to a reasonable accuracy.

Lippke (1996) made a study of transient behaviour of the DSG collector proposed by CIEMAT and DLR, and flagged probable difficulties with once-through DSG in the case of superheated steam generation.

Odeh (1999) also performed modelling of a DSG collector based on the SEGS design. Using published results for heat loss in the Luz collector, he created a heat loss correlation for the SEGS evacuated tubes, then applied the pressure drop correlation of Martinelli and Nelson as well as the internal forced convection correlation of Gungor and Winterton (as cited by Stephan 1992). Transient as well as steady-state phenomena were investigated.

Reynolds (2004) performed modelling of the CLFR collector using a similar approach to Odeh. Reynolds used a cavity heat loss correlation developed from an experimental model of the CLFR cavity, then used the Martinelli-Nelson and Stephan correlations as Odeh. Steady-state and transient results were modelled, and the conditions for steady flow regimes at the collector exit were investigated.

Natan et al (2003) produced some modelling of direct steam generation in two parallel pipes and observed some dynamic effects resulting from the parallel interconnection. Under certain conditions, the flow rates in the two pipes can become significantly different, leading to concerns that DSG collector efficiency could be compromised, or that higher-than-anticipated temperatures could be experienced in a particular pipe.

### 3. MODEL

A code-base was developed based on the C++ code used by Reynolds (2004). This code was extended and modified as described here, and a model case implemented to replicate as far as possible the design of the DISS prototype system at the Plataforma Solar de Almería.

This model uses the homogenous flow model for two phase flow in horizontal pipes (Behnia 2002). The flow regimes are predicted using the method of Barnea et al (1987). The pressure drop correlation is that of Friedel (as reported by Behnia 2002). The internal heat transfer correlation is that of Kandlikar (as reported by Lienhard 2006).

It should be noted that an error was found in earlier work (Pye 2004, Reynolds 2004, Odeh 1999). These workers used an incorrectly curve-fitted Martinelli-Nelson curve for pressures in the region 40-100 bar. The present work was performed with both the Martinelli-Nelson correlation and the Friedel correlation, but the latter was settled on because of the larger data bank used to create it, as well as the fact that it was used in the modeling work of Rheinlander (2002) and therefore can be more easily verified.

Pressure drops for two-phase flow in bends are calculated using the method of Chisholm (1980). Gate valves are considered equivalent to 90-degree bends, as recommended by Chisholm and as assumed by Rheinlander. Other minor losses (ball joints, instruments, etc.) are ignored, as by Rheinlander.

In single-phase flow, pressure drops using the iteratively solved Colebrook equation are used. Internal heat transfer is calculated using the Dittus-Boelter equation for  $Re > 11000$ , and the Gnielinski correlation for  $Re < 10000$ . For intermediate values of  $Re$ , the average of the two correlations is used, to avoid step changes in heat transfer.

The code-base also implements prediction of two-phase flow regimes using the method summarised in the paper by Barnea et al (1987), although results for this are not presented here.

The calculation of flow regimes, as well as the energy and momentum calculations, is simplified to only deal with horizontal pipes. This represents a deviation from the calculation presented by Rheinlander (2002) in that the pipes of the DISS prototype have an inclination of between 2 and 8 degrees. The effect of pipe inclination is therefore being ignored. Pressure changes due to gravitational potential are also ignored.

#### 4. PRESSURE DROP VALIDATION

The report of Rheinlander (2002) gives pressure drops through the DISS prototype system for the range of operating conditions, which are reproduced here as Table 1. This gives the ambient temperature ( $t_{amb}$ ), received solar radiation ( $DNI \cdot IAM$ , direct normal radiation multiplied by incidence angle modifier), collector efficiency ( $\eta_{coll}$ ), inlet temperature ( $t_{in}$ ), inlet enthalpy ( $h_{in}$ ), inlet mass flow rate ( $mass_{1\_in}$ ), injector mass flow rate ( $mass_{11\_in}$ ), outlet temperature ( $t_{out}$ ), outlet enthalpy ( $h_{out}$ ), and inlet pressure ( $p_{in}$ ). Also given by Rheinlander were the experimental pressure readings at a number of points in the DISS prototype system. These are not tabulated here but are presented (pressures in bar) in Figure 1 and Figure 2 plotted versus distance along the flow path (in metres).

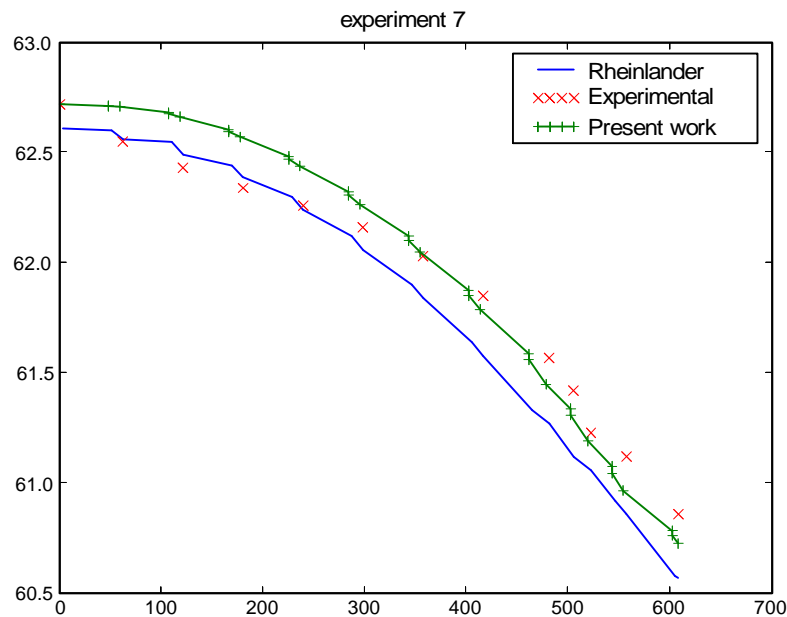
**Table 1. Experimental conditions for the cases given in the Rheinlander (2002) study.**

	$t_{amb}$	$DNI \cdot IAM$	$\eta_{coll}$	$t_{in}$	$h_{in}$	$mass_{1\_in}$	$mass_{11\_in}$	$t_{out}$	$h_{out}$	$p_{in}$
	°C	kW/m <sup>2</sup>		°C	kJ/kg	kg/s	kg/s	°C	kJ/kg	
experiment 1	28.50	0.8664	0.6940	198.10	844.6	0.494	0.000	352.6	3120.3	34.05
experiment 2	28.00	0.9560	0.7160	238.50	1030.7	0.653	0.000	322.3	2959.4	63.28
experiment 3	32.00	0.9275	0.9850	239.80	1036.9	0.814	0.000	369.5	3098.0	64.16
experiment 4	28.40	0.9040	0.6770	197.50	842.0	0.501	0.000	356.5	3128.8	34.52
experiment 5	25.50	0.7631	0.6385	193.44	823.8	0.401	0.000	335.3	3079.5	32.94
experiment 6	30.10		0.8530	212.40	909.3	0.732	0.000	279.6	2933.5	37.56
experiment 7	28.60	0.7506	0.7730	238.40	1030.3	0.561	0.000	302.7	2892.7	62.72
experiment 8	26.80	0.8879	0.7480	236.70	1022.2	0.611	0.000	338.2	3008.1	63.06
experiment 9	27.48	0.8833	0.8260	237.50	1026.0	0.645	0.000	367.0	3089.5	63.56
experiment 10	35.70	0.9068	0.7740	265.60	1161.7	0.739	0.000	338.6	2874.4	102.40
experiment 11	18.68	0.8978	0.8185	202.00	862.2	0.581	0.022	355.6	3126.5	35.36
experiment 12	27.80	0.9032	0.5900	205.60	878.3	0.445	0.000	352.4	3120.2	33.47

In order to validate pressure drops using the Rheinlander data, net absorbed heat was adjusted to match the values given in the experimental data. It was not possible to validate the heat absorption and heat loss model using the Rheinlander report, because these parameters were not fully specified in his report.

Using balanced overall absorbed heat, the pressure drop profile for Rheinlander's 'experiment 7' is shown in Figure 1. The results for the full set of Rheinlander model cases are shown in Figure 2.

These results show that the present model reproduces the pressure drops in the DISS experiments as accurately as the Rheinlander approach. There is some discrepancy at the inlet: Rheinlander's model uses a lower value of inlet pressure than was specified in the experimental data, but the reason for this is not clear. The present values are otherwise consistent with the Rheinlander model, and agree well with the experimental results. Experiments 3 and 10 show the worst agreement. These cases represent high mass flow rates coupled with high inlet temperatures. In both of these cases, the modelling of Rheinlander gave the same overestimation of pressure drop as the present model. In the absence of more information, it is difficult to surmise whether experimental error or some deficiency in the model is to blame here.



**Figure 1. Pressure drops (bar) versus flow path distance (m) is plotted for ‘experiment 7’ from the Rheinlander report. This plot shows that the overall experimental pressure drop is accurately reproduced by the present model, although there appears to be some deviation at the inlet (in Rheinlander’s modelling) and in the sub-cooled and low-quality saturated regimes in the flow.**

From Figure 1 it can also be concluded that minor losses (the vertical sections in the pressure-versus-distance plot) give a significant contribution to the overall pressure drop. Earlier validation work by Reynolds did not include these minor losses.

## 5. CONCLUSION

Greater detail was added to an earlier computational model that attempted to reproduce the experimental results of Rheinlander (2002). Addition of minor losses and connecting pipe-work, as well as the switch to using of the Friedel two-phase pressure drop model instead of that of Martinelli and Nelson, gave an overall computational model that correlates well with experimental pressure drops in most cases. The computational model from the present work can therefore be applied with some confidence to the modelling problems of the CLFR collector.

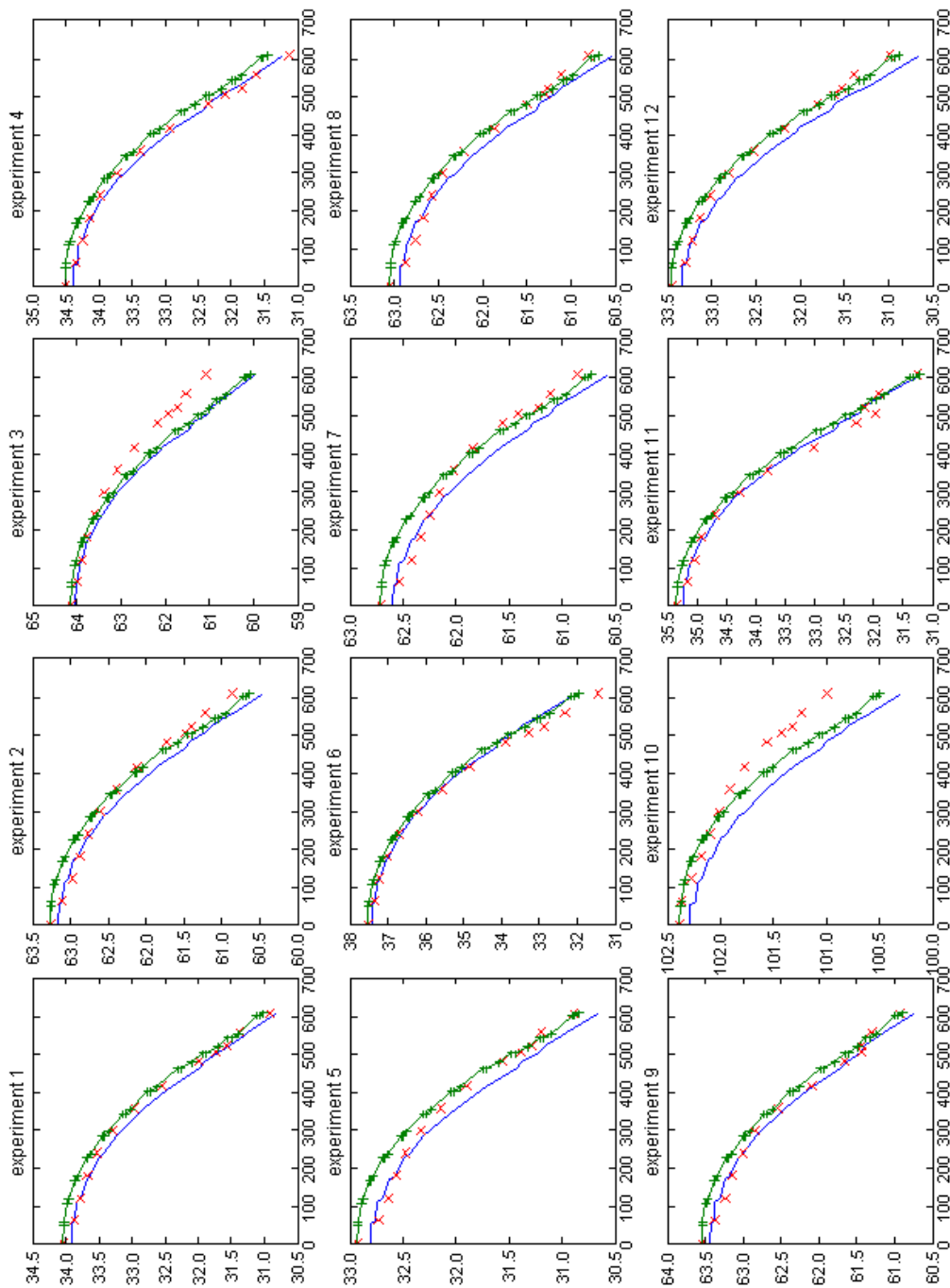


Figure 2. Pressure drop (bar) versus flow path distance (m) for the range of test cases published by Rheinlander.

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