Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 133 (2016) 567–585

SOLAR ENERGY

www.elsevier.com/locate/solener

Numerical investigation of severe slugging under conditions of a parabolic trough power plant with direct steam generation

A. Hoffmann [a,*], T. Hirsch [b], R. Pitz-Paal [c]

[a] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Resource Ecology, Bautzner Landstraße 400, 01328 Dresden, Germany*
[b] *German Aerospace Center (DLR), Institute of Solar Research, Wankelstrasse 5, 70563 Stuttgart, Germany*
[c] *German Aerospace Center (DLR), Institute of Solar Research, Linder Höhe, 51147 Köln, Germany*

Received 18 September 2015; received in revised form 14 March 2016; accepted 8 April 2016
Available online 3 May 2016

Abstract

The present study reveals a numerical investigation of severe slugging with the system code ATHLET. It is aimed to close knowledge gaps about the two-phase flow within the connection pipes of two adjacent collectors in a solar thermal power plant with direct steam generation. The underlying ATHLET model provides a one-dimensional 6 equation model with a mass, momentum and energy equation for each phase, respectively. This comprehensive model provides all features for the examination of water steam flows in this type of power plants. A validation of ATHLET for severe slugging conditions is performed and the obtained periods of severe slugging as well as the pressure amplitudes are in good agreement with experimental data. The probability of severe slugging is studied for numerous flow conditions and geometric conditions which are close to the operation conditions and the piping system at the DISS test facility at the Plataforma Solar de Almería, Spain. Basically, larger vertical and downwards inclined pipe sections increase the probability of severe slugging. Severe slugging can be strongly suppressed by a high pressure operation. In a pipe geometry that shows easily severe slugging a pressure of $P \geqslant 60$ bar prevents severe slugging. In the case of a specific pipe geometry of the DISS test facility, a pressure of $P \geqslant 30$ bar is sufficient to have a non-oscillating flow behaviour.

Keywords: Severe slugging; Parabolic trough; Direct steam generation; ATHLET

1. Introduction

1.1. Background severe slugging

Multiphase flow issues are present in a wide range of applications which are for instance related to power stations, chemical process equipments, oil and gas production or process engineering. The unsteady and cyclic multiphase flow behaviours attract a particularly high interest, due to a potentially negative impact on the operation of the system, the controllability of the system or the stresses on the system components.

The flow phenomenon of severe slugging as terrain-induced slugging is one of the undesired flow situations. It is typified by an strongly unsteady character and arises in pipeline riser systems which are fed with a multiphase flow such as water–air mixtures. Low liquid and gas flow rates usually lead to an intense characteristic of severe slugging. The gravity force in the riser and the compressibility of the gas phase in the pipeline enable a persistent accumulation of liquid in the riser and blowout of this long liquid slug. This procedure is accompanied by large-amplitude pressure fluctuations and an irregular gas and liquid flow rate (Schmidt et al., 1980; Schmidt et al., 1985). The basics

* Corresponding author.
E-mail address: alexander.hoffmann@hzdr.de (A. Hoffmann).

http://dx.doi.org/10.1016/j.solener.2016.04.012
0038-092X/

Nomenclature

Acronyms

ATH	ATHLET
DSG	direct steam generation
EPE	endpoint of evaporation
PSA	Plataforma Solar de Almería
SS1	severe slugging type: 1
SS2	severe slugging type: 2
SS3	severe slugging type: 3
STB	stable flow
USO	unstable oscillations

Greek symbols

α	volume fraction
α_{mod}	estimated gas volume fraction choke valve
β	pipe inclination
ϵ	pipe roughness
ψ	mass exchange
ρ	density
ρ_{mix}	mixture density
τ	shear stress
ζ	dimensionless form loss coefficient

Roman symbols

ΔP	pressure difference/loss
$\dot{m}$	mass flow rate
$\dot{V}_L$	volumetric liquid flow rate
$\dot{x}$	quality
$\overline{a_{\Delta P}}$	averaged amplitude of the pressure difference
A	cross-sectional area
C	single-phase choke coefficient
D	diameter
g	gravitational constant
h	enthalpy
h_{riser}	height of vertical pipe
k_v	k_v-value (flow resistance)
l	length
L_k	length of pipe sections with $k = 1, 2, 3, 4, 5$
l_{slug}	length of liquid slug
m	time lag
N	number of samples
P	pressure
R_{xx}	autocorrelation function
S	perimeter
S_M	momentum source term
T	period
t	time
U	velocity
U_Γ	mass transfer velocity
U_{GS0}	superficial gas velocity atmospheric conditions
U_{mix}	mixture velocity
U_S	superficial velocity
z	Axial pipe coordinate

Subscripts

amb	ambient
G	gas
i	interface
L	liquid
w	wall

of severe slugging have been introduced about 30 years ago by Schmidt et al. (1980), Schmidt et al. (1985), Taitel (1986) and Fabre et al. (1990) with the intention to tackle problems during the oil and gas production whereas the oil and gas industry is still the largest research area of severe slugging. Beside that, nuclear power plants under loss of coolant accident conditions show severe slugging as well which is called loop seal clearing (Schäfer, 2001; Krepper and Prasser, 1999).

In the present paper the relevance of severe slugging for water-steam flows in parabolic trough power plants with direct steam generation is investigated numerically. The prerequisite for the occurrence of severe slugging is a pipe geometry consisting of a horizontal or downwards sloped pipe, called pipeline, followed by a pipe with a positive inclination, called riser and a following separator at mostly constant pressure. At the inlet of the pipeline a constant and low mass flow rate of the liquid and gas phase is imposed. A stratified flow develops in the pipeline which facilitates severe slugging and sometimes is required for an unsteady flow (Fabre et al., 1990). In general terms, severe slugging can be described in four steps which depict a full cycle (Taitel, 1986):

1. Slug formation: The liquid phase blocks the entrance of the riser. The hydrostatic pressure gain due to liquid fallback in the riser and the fed mass flow of liquid phase into the pipeline is larger than the gas pressure increase due to the low gas mass flow rate. The liquid phase is accumulated in the riser.
2. Slug production: The riser is completely filled with the liquid phase and liquid flows into the following separator.
3. Blowout: The expansion of the gas phase in the pipeline under constant pressure conditions causes the penetration of the gas phase into the riser and powerfully pushes the liquid slug out of the riser.
4. Blowdown: When the gas phase reaches the separator a fast pressure compensation appears. Afterwards, liquid fallback may occur and a new cycle starts.

The pressure history that belongs to the cycles of severe slugging can be seen basically in Fig. 5a, see Baliño et al.