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Experimental and theoretical studies on density wave instabilities in helically coiled tubes

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ABSTRACT

This paper reports on the advancement in the study of thermal-hydraulic dynamic instabilities with reference to the helical-coiled tube geometry.

A full-scale open-loop experimental facility simulating a helically coiled steam generator was built and operated at SIET labs in Piacenza (Italy). The facility comprises two helical tubes (1 m coil diameter, 32 m length, 8 m height), connected via lower and upper headers. Nearly 100 flow instability threshold conditions were identified, in a test matrix of pressures (80 bar, 40 bar, 20 bar), mass fluxes (600 kg/m^2 s, 400 kg/m^2 s, 200 kg/m^2 s), inlet subcooling (from −30% up to ∼0), and inlet throttling (four different entrance resistance conditions). The long test section feature and the helical-coiled tube geometry render the present facility a quite unique test case in the outline of two-phase flow instability experimental studies. Parametric effects of the operating pressure, flow rate, inlet subcooling and inlet throttling on the threshold power are discussed. The period of oscillations is also discussed. Superimposition of Density Wave Oscillations (DWOs) with Ledinegg flow excursions is finally described.

Theoretical modelling of DWO occurrence in helical pipes was addressed by means of a lumped parameter analytical model, which was exploited to highlight some peculiarities of DWO phenomena and respective stability boundary with respect to classical straight geometry. In the end, numerical simulation results with RELAP5/MOD3.3 code were compared.

1. Introduction

The utilisation of once-through helically coiled Steam Generators (SGs) is well established in the framework of deployment of integral Small-medium Modular Reactors (SMRs), hosting all the primary system components inside the reactor vessel, thanks to compactness and higher efficiency in heat transfer [1]. Within the thriving research area represented by the modelling of two-phase flow behaviour in a helical channel, lots of experimental works are available on two-phase pressure drops [2–11] and the enhanced heat transfer characteristics of a helical tube [12–16]. On the other hand – up to our knowledge – no systematic experimental campaign has been carried out investigating the onset and the frequency of thermal-hydraulic instabilities within helical coil tubes for steam generator applications.

When considering thermal-hydraulic instabilities, Density Wave Oscillation (DWO) kind is frequently referred to. It is well known that DWOs are induced in a boiling system by the interaction between the single-phase and two-phase flow pressure drops, the inlet mass flow rate and the void fraction distribution [17,18]. Parallel channel boundary condition (commonly established in a steam generator tube bundle) is sufficient to maintain imposed the pressure drop across the channels, such to trigger the multiple feedback effects that are at the source of the instability inception. Key role is played by the void propagation time delay in the two-phase region. At sufficiently large values of the void fraction (i.e., exit thermodynamic quality), any small fluctuation in the inlet velocity may lead to large fluctuation of the two-phase frictional pressure losses, due to fluctuation of density and flow [19,20]. These perturbations propagate slowly in the two-phase region and hence destabilise the system.

Abbreviations: DP, differential pressure; DWO, Density Wave Oscillation; IRIS, International Reactor Innovative and Secure; RELAP, Reactor Excursion and Leak Analysis Program; SG, steam generator; SIET, Società Informazioni Esperienze Termoidrauliche (Company Information and Experiences on Thermalhydraulics); SMR, Small-medium Modular Reactor; UVUT, Unequal Velocity Unequal Temperature.

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Nomenclature

A	tube cross-sectional area (m^2)
D	coil diameter (m)
d	tube inner diameter (m)
f	single-phase friction factor (Darcy) (–)
G	mass flux (kg/m^2 s)
g	acceleration of gravity (m/s^2)
H	tube length (heated zone) (m)
H_R	riser length (unheated zone) (m)
h	specific enthalpy (kJ/kg)
k	concentrated loss coefficient (–)
N_{pch}	phase change number ($Q/(\Gamma h_{fg})\cdot v_{fg}/v_f$) (–)
N_{sub}	subcooling number ($\Delta h_{in}/h_{fg}\cdot v_{fg}/v_f$) (–)
P	pressure (bar)
Q	power (kW)
Q'''	power per unit volume (kW/m^3)
Re	Reynolds number (Gd/μ) (–)
T	period of oscillations (s)
T_{in}	inlet temperature (°C)
T_W	wall temperature (°C)
t	time (s)
v	specific volume (m^3/kg)
w	velocity (m/s)
X_{tt}	Lockhart–Martinelli parameter ($((1-x)/x)^{0.9}\cdot(\rho_g/\rho_f)^{0.5}\cdot(\mu_f/\mu_g)^{0.1}$) (–)
x	thermodynamic quality (–)
z	tube abscissa (m)

Greek symbols

α	void fraction (–)
Γ	mass flow rate (kg/s)
Δh_{in}	inlet subcooling (enthalpy units) (kJ/kg)
ΔP	pressure drops (Pa)
θ	channel inclination angle (with horizontal direction) (°)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	mixture transit time (s)
Φ^2	two-phase friction factor multiplier (–)
Ω	reaction frequency ($Q/(AH)\cdot v_{fg}/h_{fg}$) (1/s)

Subscripts

cr	transition between laminar and turbulent
el	electrical
ex	exit
f	saturated liquid
$frict$	frictional
g	saturated vapour
$grav$	gravitational
in	inlet
l	only-liquid (liquid phase at its actual flow rate)
lo	liquid-only (liquid phase with total flow rate)
$loss$	heat losses
$proc$	experimental procedure
s	straight tube
1ϕ	single-phase region
2ϕ	two-phase region

It is just mentioned that DWOs and more generally two-phase flow instabilities have been studied since the 60s. The large amount of theoretical and experimental works on the subject is collected in different literature reviews [17,21,22]. Amongst the many experimental researches dealing with straight tubes, a systematic study on the onset and the frequency of this type of oscillations at various system conditions was provided by Saha et al. [23] using a uniformly heated single boiling channel with bypass, and by Masini et al. [24] working with two vertical parallel tubes. In the recent years, some Chinese researches [25] experimentally studied the flow instability behaviour of a twin-channel system, using water as working fluid. However, a small test section with limited pressure level (maximum pressure investigated was 30 bar) was considered; systematic execution of a precise test matrix, as well as discussions about the oscillation period, are lacking.

In order to study the instability behaviour of a whole steam generator, made in principle by numerous parallel tubes working roughly with constant ΔP across, the experimental apparatus may be designed with just two parallel tubes connected by two headers. It is known [17–19] that, when two parallel channels are fed through a common plenum preceded by a common supply path, it is generally the heated channel alone, rather than the entire system, which reaches unstable conditions. Threshold conditions (mainly the limit power) obtained with a twin-channel system (the experimental facility) apply for the corresponding multi-channel system (the steam generator).

The present work focuses on the investigation of the influence of the helical shape on instability occurrence (through the centrifugal field induced by tube bending) by providing an extensive experimental database for model validation. The influence of a long test section on instability thresholds is also addressed. The results of the experimental campaign are finally interpreted with a simple analytical model developed for the prediction of DWO phenomena.

2. The experimental facility

The experimental facility, built and operated at SIET labs [26], is an extension of an electrically heated test section used for the study of the thermal-hydraulics of a helically coiled SG tube [11,27] and the assessment of a passive heat removal system based on natural circulation [28]. Fig. 1 describes the facility, provided with two electrically heated helical coil parallel tubes. The main geometrical data are listed in Table 1. Coil diameter (1 m) was chosen as representative of a mean value of IRIS SG tube [29], while tube inner diameter (12.53 mm) is the commercially scheduled value nearer to IRIS real value (13.24 mm). The heated tubes are thermally insulated by means of rock wool. It is pointed out that the thermal losses were previously measured via runs with single-phase hot pressurized water flowing inside the steam generator, and estimated as a function of the temperature difference between tube external wall and the environment [27].

The whole facility is made by a supply section and a test section. The supply section feeds demineralised water from a tank to the test section by means of a centrifugal booster pump and a feed water pump, i.e. a volumetric three cylindrical pump with a maximum head of about 200 bar. The flow rate is controlled by a throttling valve (V3) positioned downwards the feed water pump and after a bypass line. System pressure control is accomplished by acting on a throttling valve (V4) placed at the end of the SG.

An electrically heated preheater is located before the test section, and allows creating the desired inlet temperature. The test section is electrically heated via Joule effect by DC current. Two distinct, independently controllable and contiguous sections are provided. For instability experiments, power was supplied only to the first section (24 m), instead the second section (8 m) worked as a riser unheated section.

Each tube is provided at inlet with a calibrated orifice (with a differential pressure transmitter) used to measure the flow rate