Time-Frequency Analysis of a Thermally Induced Pulsating Slug Flow

Roberta Perna[1], Mauro Mameli[1], Luca Pietrasanta[2], Marco Marengo[2], Sauro Filippeschi[1*]

[1]Department of Energy, Systems Land and Construction Engineering, University of Pisa, Largo L. Lazzarino, Pisa, Italy.
[2]Advanced Engineering Centre, School of Computing, Engineering and Mathematics, University of Brighton, Lewes Road, BN2 4GJ Brighton, UK.

*sauro.flippeschi@unipi.it

Keywords: Time Frequency Analysis, Slug Flow, Pulsating Heat Pipe.

Abstract

The thermofluidic operation of two-phase heat transfer devices is affected by thermally induced fluid oscillations of unknown frequency and amplitude. In line with previous studies, the time-frequency analysis of experimental signals is performed to investigate the existence of local characteristic frequencies. This work applies the wavelet transform to the evaporator fluid pressure signal of a passive two-phase heat transfer which can work as a Thermosyphon or as a Pulsating Heat Pipe, depending on the gravity acceleration. The results, obtained by means of a parabolic flight campaign, shows that the local characteristic frequencies are present only during the microgravity phase and in a frequency range from 0.8 to 2 Hz. Understanding the complex phenomena related to thermally induced oscillation is essential for the development of reliable heat transfer models and robust design tools for Pulsating Heat Pipes.

Introduction

Thermally induced oscillations in two phase slug flows largely affect the operation of heat transfer devices such as microchannel heat exchangers and wickless heat pipes, also known as Pulsating Heat Pipes (PHP). In the first case, these phenomena may lead to flow instabilities that are often detrimental for the device operation, causing a flow reversal to the inlet manifold (Saha and Celata, 2016), while, in the second case, they constitute the vary basic working principle (Rao et al., 2017). Furthermore, since in PHPs the mass flow rate is not a given input, the flow oscillation parameters (amplitude, frequency) are not known a priori and they are too complex to be derived only from physical and analytical considerations. For this reason, the signal frequency analysis of experimental data has been used in the literature to investigate the existence, for instance, of dominant frequencies in the flow motion.

The spectral analysis of PHPs by means of Fast Fourier Transforms (FFT) performed so far in the literature, shows contradictory results as described by Mameli et al. (2014). Since it is expected that the flow signal parameters may vary in time, the time frequency analysis seems a more suitable tool for catching the local dominant frequencies. Zhao et al. (2011) and Fairley et al. (2015) were, to the author's knowledge, the first to apply the time-frequency analysis to the temperature of the PHP envelope. While in the first work it is difficult to appreciate quantitative results in terms of dominant frequencies, the second clearly shows several spectrum peaks around 0.1Hz.

In the light of the promising results obtained so far in the literature, but also believing that the PHP envelope and its thermal inertia acts as a low-pass filter to the signal, the present work proposes to apply the wavelet transform on the fluid local pressure signal of a PHP, to demonstrate that the detected frequencies are not spurious frequencies introduced by the wavelets, but fully related to the physics.

A special hybrid heat pipe has been chosen: it is working as closed loop Thermosyphon (TS) when assisted by gravity and as a PHP in microgravity conditions (Mameli et al. 2018). The fluid local pressure signal of such a hybrid device is analysed by means of the wavelet transform tool, showing the existence of local characteristic frequencies only during the microgravity phase, confirming that the time frequency analysis can be a suitable tool for the investigation of thermally induced oscillations and that the actual characteristic frequencies may be higher than the one found in the literature so far.

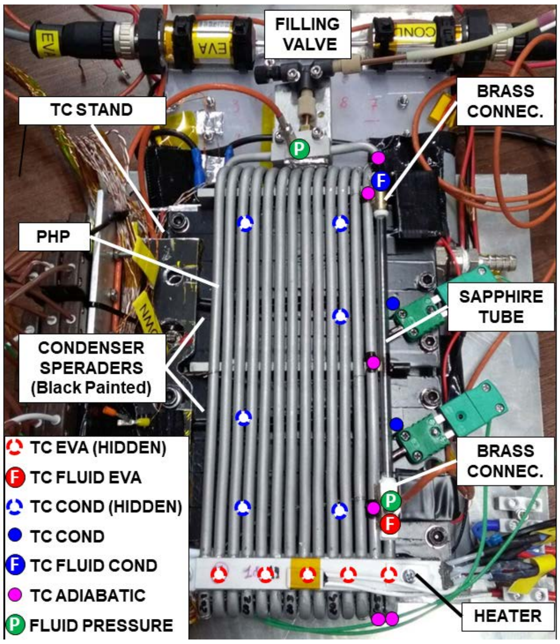

Figure 1: Experimental test cell.

Experimental facility

The hybrid TS/PHP consists of an annealed aluminum tube with an inner/outer diameter of 3/5 mm. The tube is folded in a single loop staggered 3D configuration with fourteen turns in the evaporator zone as shown in Figure 1.

An aluminum T-junction allows to close the loop and hosts one pressure transducer (Keller® PAA-M5-HB, 1 bar abs, 0,2% FSO accuracy) along with the vacuum and filling port. Two brass connections allow to embed a sapphire (transparent) tube insert and to host two K-type micro-thermocouples for the fluid temperature measurement, as well as one pressure transducer close to the evaporator section. Two ceramic ohmic heaters supply from a minimum of 18W to a maximum of 180W, corresponding to an average wall to fluid heat flux from 1.10 to 11.43 W/cm^2. The condenser zone is cooled down by means of eight Peltier cells and cold plate temperature control system. Five T-type thermocouples are located in between the spreader and the heater, one Pt-100 directly on the heater; eight on the tube external wall; six between the cold side of the Peltier cells and the condenser; two on the condenser spreader just behind the sapphire tube as shown in Figure 1. The device is partially filled with 22 ml of FC-72 (50% vol.). The test rig is then loaded on an Airbus A310 and a total of 93 parabolic trajectories are performed over the three days of flight. The device is oriented in bottom heated mode (the main acceleration field in the flow path direction). During the thermal characterization, the device is heated up at the desired power level before the occurring of the microgravity period, and the power level is kept constant for the whole sequence of parabolae, the pressure signals are acquired at 200Hz.

Results and Discussion

Figures 2 shows three synchronized subplots in a time range of 100s, capturing the 20th parabola of the first day, with a total heat load of 134 W at the evaporator.

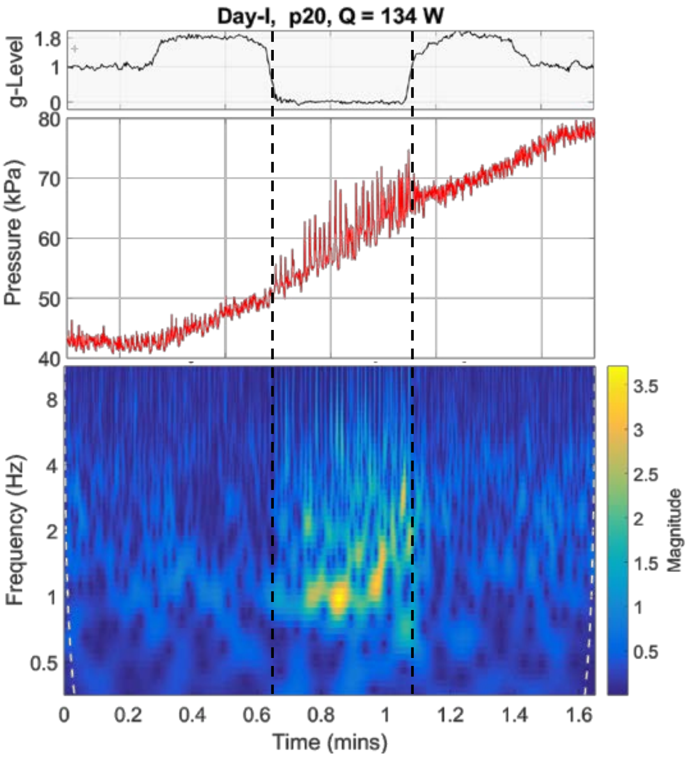

Figure 2: a) Gravity acceleration temporal trend during a parabola; b) Evaporator fluid pressure signal; c) Wavelet transform of the pressure signal.

The temporal profile of the gravity acceleration (Fig 2a) reveals the different phases of the parabolic trajectory: the first hyper-gravity period (~22s at 1.8g); the micro-gravity period (~22s at 0±0.01g) and a second hypergravity period similar to the first one. Figure 2c shows the fluid local pressure measured just above the evaporator section. After the occurrence of microgravity, the device enters in the PHP working mode characterized by the thermally induced slug-plug oscillating flow: the pressure peaks are higher in amplitude and seem coarser and more regular. Finally, figure 2c shows the Morlet wavelet transform applied to the evaporator pressure signal, confirming that the higher magnitude peaks (yellow spots) occur during the microgravity period and they are between 0.8 and 2 Hz. This result is repeatable for all the parabolae and for the different heat loads, with amplitude spectrum increasing with the heat input levels.

Conclusions

The wavelet transform has been applied to the fluid pressure signal of a special type of passive wickless two-phase heat transfer device that operates as a closed loop Thermosyphon in gravity assisted mode, while it works as a Pulsating Heat Pipe during microgravity. The results show that frequency spectrum peaks between 0.8 and 2 Hz appear only during the microgravity period. The full paper will show how the oscillation frequencies and amplitudes are linked to the different heat loads.

Acknowledgments

The present work is carried forward in the framework of the ESA MAP Project INWIP and the EPSRC UK HyHP Project (EP/P013112/1). Thanks to the NOVESPACE team in Bordeaux; to R. Manetti, M. Ciampalini, F. Peticca, D. Della Vista for their essential technical contribution; to Dr. D. Mangini, Dr. N. Miche, A. Catarsi, M. Bernagozzi and M. Pozzoni for their support during the campaign. Special thanks to Dr. B. Toth for his constant interest and support.

References

Saha S.K., Celata G.P., Instability in Flow Boiling in Microchannels, SpringerBriefs in Applied Sciences and Technology, (2016).

Rao M., Lefèvre F., Czujko P., Khandekar S., Bonjour J., Numerical and experimental investigations of thermally induced oscillating flow inside a capillary tube, Int. J. of The. Sci., 115, 29-42, (2017).

Mameli, M., Marengo M., Khandekar S., Local heat transfer measurement and thermo-fluid characterization of a pulsating heat pipe, Int. J. of The. Sci. 75, 140-152, (2014).

Zhao N., Ma H., Pan X., Wavelet Analysis of Oscillating Motions in an Oscillating Heat Pipe, ASME 2011 Int. Mech. Eng. Congress & Expo., Denver, USA, Nov 11-17, 2011.

Fairley J.D., Thompson S.M., Anderson, D. Time-frequency analysis of flat-plate oscillating heat pipes, Int. J. of The. Sci. 91, 113-124, (2015).

Mameli M., Catarsi A., Fioriti D., Mangini M., Pietrasanta L., Miche N., La Foresta M., Caporale L., Marengo M., Di Marco P., Filippeschi S, Large Diameter Pulsating Heat Pipe for Future Experiments on the International Space Station: Ground and Microgravity Thermal Response, Joint 19th IHPC and 13th IHPS, Pisa, Italy, June 10-14, 2018.