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Time–frequency analysis of flat-plate oscillating heat pipes

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ABSTRACT

Time-varying surface temperatures of two flat-plate oscillating heat pipes (OHPs), one with Tesla valves and one without, were analyzed in the time–frequency domain using the short-time Fourier and Hilbert–Huang transforms. Tesla valves were installed along the channel structure of the OHP for the purpose of rectifying the oscillatory internal flow field, thereby enhancing heat transfer. Spatial-averaged surface temperatures in the evaporator region of both OHPs were investigated in the time–frequency domain at three separate heat inputs in order to detect salient effects of the Tesla valves. In all cases, the temperature signals from both OHPs were found to contain intermittent, aperiodic oscillations with most energy concentrated at frequencies in the 0–200 mHz range. The energies of oscillations in both OHPs were found to decrease with increases in the heat input, suggesting more consistent inter-channel flow circulation at these heat inputs heat inputs. The non-valved OHP temperature signals contained oscillations of larger amplitude and over a broader frequency range than the valved OHP temperature signals, indicating that the Tesla valves reduced the occurrence of intermittent high-energy oscillations in the OHP evaporator surface temperature.

1. Introduction

The decreasing size and increasing power dissipation of electronic components continues to drive the demand for high heat flux transport devices. The oscillating heat pipe (OHP), as shown in Fig. 1, is one such device that is passive in nature (contains no moving parts). It takes advantage of phase change heat transfer and cyclic/pulsating flows to achieve a high heat transfer rate. OHPs are typically constructed by bending capillary tubing into a serpentine shape or by machining mini-to-micro-sized channels into a block of material. Once constructed, the OHP is evacuated, filled to a certain volume (i.e. filling) ratio with working fluid, and hermetically sealed. The diameter of the channels is made small enough to ensure that surface tension forces are dominant over gravitational forces.

During operation, heat (Q) is applied to the evaporator region of the OHP. Once a minimum heating rate is achieved, the working fluid begins to evaporate, generating vapor bubbles (vapor plugs) within the channels of the OHP. Pressure differences between the channels are created by the formation, expansion, contraction, and collapse of these vapor plugs. The combined effect of these pressure differences and surface tension forces causes volumes of liquid (liquid slugs) to remain intact and flow within the OHP. The two-phase fluid flow carries heat through the adiabatic region and into the condenser, where the heat is removed from the OHP. However, because the formation of vapor plugs occurs near-randomly, flow within the OHP is not steady and the vapor pressure along the evaporator is not uniform. This results in a pseudo-chaotic, oscillatory liquid flow pattern that is accompanied by varying degrees of circulation (net displacement flow) [1,2]. The dominant, oscillatory component of the vapor flow results in little to no net displacement of the liquid and this reduces the prevalence of circulatory flow. It has been found that liquid circulation greatly improves OHP performance by allowing for increased convective heat transfer [3–5]. Akachi [6] initially suggested the use of check valves to promote circulation within an OHP for better thermal performance. The OHP's time-varying temperature field is strongly coupled with the internal flow behavior [7–9]. Under certain conditions—such as excessive heat inputs and/or relatively low filling ratios—'dry-out' can occur in the evaporator, partially or completely impeding flow through the capillary tubes/channels. During dry-out, vapor pressure along the tube/channel sections is near uniform, leading to superheating of static vapor and the

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Nomenclature

$a(t)$	amplitude of the analytic representation of a time series $x(t)$
$c(t)$	intrinsic mode function
$H(t, \omega)$	Hilbert–Huang amplitude spectrum
$\mathscr{H}$	Hilbert transform
$h(\omega)$	marginal Hilbert–Huang spectrum
L	window length
N	number of sample points
Q	rate of heat transfer
$r(t)$	empirical mode decomposition residue
$Re(z)$	real part of the complex number z
$S[n, \omega]$	short-time Fourier transform energy spectrum
T	temperature
t	time
$w[n]$	windowing function
$X[n, \omega]$	short-time Fourier transform of a time series $x[n]$
$x[n]$	discrete time series
$x(t)$	continuous time series
$z(t)$	analytic representation of a time series $x(t)$
Greek	
ω	frequency
$\theta(t)$	phase of the analytic representation of a time series
Subscripts	
avg	average
e	evaporator

inability of condensate to return. Since flow is impeded, the OHP is unable to operate in the convective mode and heat transfer occurs predominantly via conduction (sensible heating of vapor and liquid). This leads to increased thermal resistance and significant evaporator surface temperature rises. At relatively lower heat inputs, sharp evaporator temperature rises can also occur due to vapor pressure balancing between channels and the presence of a significant amount of liquid is in the evaporator.

Several methods have been employed to investigate and characterize the underlying oscillatory behavior of OHP temperature fields, or 'signals' [5,10–12]. Xu and Zhang [10] compared the power spectral densities of temperature signals in the evaporator, condenser, and adiabatic regions of a tubular OHP exposed to various heat inputs. At high heat levels the power spectral densities in all three regions contained peaks, indicating quasi-periodic behavior. The peaks were observed at a temperature oscillation frequency of approximately 0.46 Hz for all three regions. It was concluded that this frequency corresponded to the frequency of the oscillatory component of the fluid's motion within in the capillary tubes.

Zhao et al. [11] also analyzed the spectral content of the OHP evaporator temperature signals. It was demonstrated that employing a classical Fourier analysis does not provide any insight into the time-varying nature of the oscillatory frequency of the temperature signals. In order to examine this behavior, the discrete wavelet transform was used to decompose OHP evaporator temperature signals into components that oscillated at different frequencies and showed variations in amplitude over time. The results of this analysis indicated the presence of multiple oscillation modes in the OHP flow pattern.

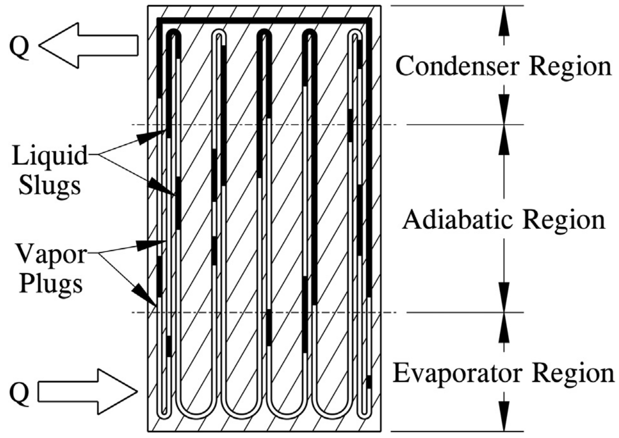

Fig. 1. Flat plate OHP during operation.

More recently, Peng et al. [12] analyzed flow oscillations within a theoretical OHP using finite element methods. The Hilbert–Huang transform (HHT) was used to perform spectral analysis of a nonlinear liquid slug velocity signal. The HHT is an empirical, time–frequency analysis technique that performs well; even for data that are non-stationary and/or nonlinear [13], such as the simulated slug velocity signal. Using the HHT, it was shown that the frequency and amplitude of oscillations in the slug velocity signal vary over time. However, Peng et al. did not utilize the Hilbert–Huang transform to analyze regional temperature oscillations within the numerically-simulated OHP.

Thompson and Ma [5] performed statistical analyses to compare the evaporator temperature signals of flat-plate OHPs with and without Tesla valves. Tesla valves are mini-to-micro-scale structures that promote flow in one direction by redirecting reverse-flowing fluid in order to create a pressure gradient that favors forward flow. Unlike typical check valve designs, the Tesla valve does not require moving parts. Thompson and Ma found that the temperature signals of both OHPs were not adequately modeled by unimodal Gaussian distributions, leading to the conclusion that multiple frequency modes must be present within the signals [5]. On the observation that the temperature signals displayed multimodal properties, a Gaussian mixture model was used to estimate the probability density functions of the signals; it was found that the estimated number of mixture components for the OHP with Tesla valves was typically lower than that of the OHP without Tesla valves. The Shannon entropy and kurtosis of the temperature signals were also analyzed. The OHP with Tesla valves typically yielded higher Shannon entropy and kurtosis, which was thought to be the result of increased circulatory flow within the evaporator.

The current investigation will extend upon the aforementioned works. Note that the methods utilized by Xu and Zhang [10] were derived from a Fourier transform of the temperature signals, resulting in idealizing the signals as 'stationary'. Since their data were approximately stationary, their analysis methods yield meaningful results. However, OHP temperature signals, in general, are not as well-behaved as the signals observed by Xu and Zhang [14–16]. Different combinations of working fluids, channel geometries, fill ratios, and heat inputs can cause the temperature signals to become non-stationary and aperiodic. In these cases, utilizing the methods of Xu and Zhang can give misleading results; 'time–frequency' analysis techniques are more appropriate for examining oscillations in such temperature signals.