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Research Paper

Recognition of steam jet condensation regime in water pipe flow system by statistical features of pressure oscillation

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HIGHLIGHTS

- Massive experimental data on steam jet condensation in water pipe flow system.
- Clear interrelations between condensation regimes and features of pressure signal.
- Method of extraction features and their ability evaluation of regimes classification.
- Support vector machine is adopted to the clusters for construction of classifiers.
- Satisfactory recognition rate of condensation regimes by pressure signal is gained.

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ABSTRACT

Recognition of unstable and harmful condensation regimes in liquid pipe flow system can promote a higher level of flow assurance in liquid propellant rocket engine. However, challenges are encountered in extracting distinguishable characteristics from pressure oscillation signals which commonly contains plentiful information strongly associated with various condensation regimes. This article attempts to set up a simple and practical approach of recognizing the steam jet condensation regime in water pipe flow system based on statistical features of pressure oscillation. The recognition procedure was performed in three major steps. Initially, twelve statistical features of pressure oscillation in time-domain (probability density function) and frequency-domain (power spectrum density) were chose. Subsequently, principal component analysis was implemented to obtain the clear interrelations between condensation regimes and statistical features of pressure oscillation signal, and then to extract useful features for establishing condensation regimes clusters for classification in the selected features space. Finally, least squares support vector machine was adopted to the clusters for construction of classifiers to forecast the condensation regimes automatically. The experimental results showed that the proposed approach is feasible and effective for recognizing the steam jet condensation regime in water pipe flow system by statistical features of pressure oscillation.

1. Introduction

Direct contact condensation of vapor jet in liquid systems is frequently encountered in the energy transportation industry due to its high efficiency of heat and mass transfer, such as nuclear reactor safety system, liquid propellant rocket engine system, and solar refrigeration system, etc. [1–5]. In liquid propellant rocket engine system, the gas oxygen is directly discharged into the liquid oxygen pipeline to improve the thermal efficiency of the rocket engine [1]. From viewpoint of flow assurance, the vapor-liquid mixture in the pipeline of the engine system must be operated in a safe, reliable and efficient way throughout the design life of the rocket vehicle. However, during the operation process, gas oxygen jet and liquid oxygen multiphase mixtures transported in the pipeline system have various condensation regimes that are more complicated than the condensation regimes of vapor jet in stagnant liquid in pool. Some of the condensation regimes may lead to substantial pressure fluctuation in the fluid system, which leaves the rocket vehicle prone to longitudinal vibration. Therefore, the condensation regimes of vapor jet in liquid pipeline systems must be carefully controlled to ensure safety operation.

Substantial research has considered the condensation regime of vapor jet condensation in liquid. Chan and Lee [6] was the pioneer to establish a condensation regime diagram for steam jet condensation in water pool at low steam mass flux ($1 < G_s < 175$ kg/m^2 s).

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Nomenclature

$\boldsymbol{a_j}$	jth eigenvalue of the covariance matrix $\sum$ of $\boldsymbol{X}$
b	real number
C	penalty parameter
d_e	inner diameter of the nozzle, m
d_m	maximum diameter of the steam plume, m
D	inner diameter of the vertical round pipe, m
g	ACR threshold
G_s	steam mass flux at the nozzle exit, kg/m^2 s
$h(\cdot)$	LS-SVM classifier function
i	ordinal of data points in a test sample
$\boldsymbol{I}$	identity matrix
$K(\cdot,\cdot)$	kernel function
L_p	Lagrange function
m	dimension of feature vector
m_w	water flow rate, kg/s
n	sample number
N	data points in a test sample, 1
$\bar{p}$	mean of pressure, kPa
p_i	signal of pressure oscillation, kPa
p_i'	mean-variance standardization of p_i, 1
p_s	steam inlet pressure, MPa
p_w	water pressure at the steam injection point, MPa
R^d	set of real numbers
Re_w	Reynolds number of water flow equals to $4m_w/\pi D\mu_w$, 1
S	sample variance of p_i
$S(f)$	PSD curves
s_i	slack variables
t	time, s
T_s	steam inlet temperature, °C
T_w	water inlet temperature, °C
w	weight vector in LS-SVM
$\boldsymbol{x}$	feature parameter vector
$\boldsymbol{X}$	data matrix contained N vectors $\boldsymbol{x}$
y_i	binary class label, $y_i = \pm 1$

Greek letters

α_i	Lagrange multiplier
β_i	Lagrange multiplier
ζ_j	jth principle component
$\boldsymbol{\eta}$	mean vector of jth feature parameter $\boldsymbol{x}$
θ	angle between the nozzle center line and the pipe wall, °
λ	eigenvalue of $\sum$
μ_w	dynamic viscosity of water, m^2/s
σ	variance of normal distribution
$\sum$	covariance matrix of $\boldsymbol{X}$

Subscripts

s	the steam phase
w	the water phase

Acronyms

ACR	accumulative contribution rate
LS-SVM	least squares support vector machine
Oscil-I	Oscillation condensation I regime
Oscil-II	Oscillation condensation II regime
PC	principle component
PCA	principle component analysis
PDF	probability density function
PSD	power spectrum density
SVM	support vector machine

The interface behavior of the steam-water was recorded by high-speed films, and it was systematically classified into six different condensation regimes with the dependencies of steam mass flux and pool temperature. With the techniques of visual observation and pressure signal analyzation, Chun et al. [7] confirmed the presence of six condensation regimes for a higher range of steam mass flux up to 700 kg/m^2 s, including chugging, condensation oscillation, transitional region from chugging to condensation oscillation, bubbling condensation oscillation, interfacial oscillation condensation, and stable condensation. A. With et al. [8] proposed a three-dimensional condensation regime diagram, which not only included the traditional dependencies of steam mass flux and water subcooling but also added the nozzle diameter as the third dependency. The three-dimensional condensation regime diagram can be rationalized into a total of seven different regimes, i.e., no condensation, interfacial condensation oscillation, chugging, bubbling, conical jetting, ellipsoidal jetting and divergent jetting. Wu et al. [9] proposed a three-dimensional condensation regime diagram for sonic and supersonic steam jet condensation in water pool. The condensation regime diagram contained six condensation regimes, such as contraction shape, contraction-expansion-contraction, contraction-expansion-divergent shape, expansion-contraction shape, double expansion-contraction shape, and divergent shape. In terms of stable steam jet condensation in water flow in pipes, five different jet shapes were found, i.e., hemispherical, conical, ellipsoidal, cylinder and divergent [8,10–14].

Furthermore, many other topics associated with steam jet condensation in water include jet penetration length, heat transfer coefficient, turbulent jet flow field and jet stability. Kerney et al. [15] proposed the first jet penetration length correlation as a function of dimensionless steam mass flux and condensation driving potential, and lately many revised correlations were suggested according to various flow and test conditions [10–14,16–19]. Heat transfer coefficients were generally predicted by interfacial transportation theory and also many semi-empirical prediction correlations were proposed [7–14]. The turbulent jet flow fields were generally detected with visualization techniques of Particle Image Velocity (PIV), Planar Laser Induced Fluorescence (PLIF) and mobile thermocouple probes [13,20–23]. Both the average axial velocity and temperature profiles of the condensing jet were found to show good self-similarity feature. The stability of steam jet condensation in water in literature was largely concentrated on amplitude and dominant frequency of the pressure oscillation [24,25]. The dominant frequency was found to proportional to the water subcooling and inversely proportional to the nozzle diameter [24,25].

The aforementioned approaches of analyzing and classifying condensation regimes are generally based on either visual observation from experiments or the simplified thermal dynamical model of one or several typical condensation regimes. Noticeably, different researchers' visual observations lack quantitative or objective descriptions of different condensation regimes. Moreover, these condensation regime diagrams differ significantly among observers, especially in the condensation regime transition regions. In recent decades, statistical analysis of flow signals is appealing to researchers in the quantitative determination of the recognition criteria of flow regimes, since flow signals comprise plentiful information about multiphase flow systems [26]. This technique has been applied successfully to the flow regimes identification in the gas-liquid two-phase pipe flows. Several effective parameters dependent on the flow regimes have been selected from numbers