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A physically based, one-dimensional three-fluid model for direct contact condensation of steam jets in flowing water

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ABSTRACT

A simulation model for the direct contact condensation of steam jets in flowing water is presented. In contrast to previous empirical approaches, the model takes into account the underlying physical phenomena governing the condensation process. Condensation at the interface between the steam jet and the surrounding water is calculated according to the surface renewal theory. Entrainment of water into the steam jet is modeled based on the Kelvin–Helmholtz and Rayleigh–Taylor instability theories. The resulting steam-water two-phase flow is simulated based on a one-dimensional three-fluid model. An interfacial area transport equation is used to track changes of the interfacial area density due to droplet entrainment and steam condensation on droplets. The simulation results are in good qualitative agreement with published experimental data. In particular, the dependency of the steam jet length on the flow Reynolds number is properly reproduced. This corroborates our theory that the heat transfer coefficient at the interface of a condensing steam jet can be linked to the water flow rate via the interfacial friction factor.

1. Introduction

The direct contact condensation (DCC) of a high-velocity steam jet in subcooled water offers a highly efficient means of steam condensation and is therefore used in many industrial applications, such as thermal degasification, direct contact heat exchangers or the depressurization systems of current light water reactors. Furthermore, the phenomenon is of particular importance for the operation of steam injectors, where efficient steam condensation is crucial for stable operation.

Direct contact condensation of a steam jet in subcooled water is based on two different mechanisms: Condensation directly at the steam-water interface on the one hand, and entrainment, atomization and subsequent droplet condensation on the other hand. Condensation due to atomization can be divided into two parts. First, the interface between the steam jet and the water is disrupted due to the high velocity difference between the two phases. Waves arise, expand into the high-speed gas phase and atomize to form small liquid droplets. The large interfacial area density obtained by this turbulent mixing process then establishes the basis for rapid steam condensation. Accordingly, the initial development of the two-phase jet flow is mainly governed by the momentum transfer from the high-velocity steam to the entrained droplets, while mass and heat transfer dominate with growing interfacial area density.

Direct contact condensation in pools, i.e. in free environments, has been the subject of numerous experimental and theoretical studies. Various investigators have shown that for pool DCC, the steam plume length is mainly dependent on the steam mass flux and the temperature of the water pool [1]. In our previous work [2], we have developed a physically-based simulation model that can reproduce these dependencies.

In contrast, only little research has been devoted to DCC in channels, i.e. in flowing water. Recent experiments by Xu et al. [3] highlight a strong dependency of the jet shape and length on the water flow rate, more precisely the flow Reynolds number. This is attributed to the turbulent flow of the water surrounding the jet, which enhances the heat and mass transfer at the jet interface. The authors proposed an empirical correlation for the length of a steam jet in flowing water. However, there are no physically-based models that can predict the experimentally observed trends for channel DCC, most important the interrelation between water flow rate and steam condensation.

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Nomenclature

a	acceleration
A	cross-section
a_{if}	interfacial area density
b	wave crest thickness
c	velocity
C	constant, coefficient
c_p	specific isobaric heat capacity
d	diameter
E_0	entrainment coefficient
f	friction factor
h	enthalpy
k	wave number
l	jet penetration length
L	dimensionless jet penetration length
$\dot{m}$	mass flux
M	volume-specific total interfacial shear force
Ma	Mach number
Nu	Nusselt number
Oh	Ohnesorge number
p	pressure
Pr	Prandtl number
$\dot{q}$	heat flux
r	radial coordinate
R	radius
Re	Reynolds number
R_s	specific gas constant
s	specific entropy
t	time
$\hat{t}$	dimensionless time
T	temperature
w	speed of sound
W	channel width in stratifed flow
We	Weber number
x	mass fraction
z	axial coordinate

Greek letters

α	heat transfer coefficient
γ	proportionality factor for the vorticity layer
Γ	volumetric mass source term
δ	thickness
ϵ	volume fraction
$\tilde{\epsilon}$	relative volume fraction
λ	thermal conductivity
$\tilde{\lambda}$	wave length
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ	shear stress
Φ	interfacial area source term
ω	amplification rate

Indices

0	stagnation condition
$2ph$	two-phase flow region
32	Sauter-averaged mean value
b	burst
bbl	bubble
c	continuous phase
co	condensation
$crit$	critical condition (at sonic velocity)
d	dispersed phase
D	drag
drp	droplet
e	nozzle exit
en	entrainment
g	gas phase
H	hydraulic
if	interface property
ini	initiation
KH	Kelvin–Helmholtz
l	liquid phase
m	mixture property
RT	Rayleigh–Taylor
sat	saturation
t	turbulence
τ	shear
tot	total
w	water
$wall$	wall

This article presents a simulation model for DCC in flowing water which is capable of reproducing this relationship. The approach is based on a one-dimensional three-fluid model and accounts for the dominant physical processes of droplet condensation on the one hand, and condensation at the interface between the two-phase jet and the flowing water on the other hand. Modeling of droplet condensation has been subject of our previous work [2], so the present work focuses on the exchange processes at the jet interface. In the following, we develop physically-based transfer models for these processes. Afterwards, we describe our theoretical model, the underlying conservation equations and the required closure relations. Subsequently, we give details on our numerical implementation. Finally, the simulation results obtained with our model are compared to experimental data from the literature.

2. Development of exchange models for the jet interface

2.1. Interfacial heat transfer coefficient

There is little experimental data for the heat transfer at the interface of condensing jets. At first glance, experiments for annular condensing flow seem to be a viable alternative. However, while the geometrical configuration is indeed similar – a steam core surrounded by an annular liquid layer –, the underlying physical mechanism is different: In most experiments, the liquid annulus is formed due to steam condensation at the wall and is often dominated by gravitational effects. For this reason, it seems more appropriate to refer to experiments and models for stratified condensing flow. The geometric layout is somewhat different, but in most experiments the two phases are initially separated and thus independent of each other.

Accordingly, the heat transfer coefficient at the liquid side of the jet interface is modeled in analogy to stratified flow. A widely used approach for modeling interfacial transfer in stratified flow is the surface renewal theory [4,5], which considers the fluid motion near the interface. Based on this theory, various authors have proposed correlations for the liquid side heat transfer which follow the functional form

$$Nu_t \cdot Pr^{-0.5} = C_1 \cdot Re_t^{C_2}. \quad (1)$$

Here, $Pr = c_p \mu_w / \lambda_w$ is the Prandtl number of the liquid phase based on the specific isobaric heat capacity c_p [J/(kg K)], the

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