International Journal of Heat and Mass Transfer 68 (2014) 401–414

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat and mass transfer analogy applied to condensation in the presence of noncondensable gases inside inclined tubes

Gianfranco Caruso *, Damiano Vitale Di Maio [1]

"SAPIENZA" University of Rome, DIAEE, Corso Vittorio Emanuele II, 244 - 00186 Rome, Italy

ARTICLE INFO

Article history:
Received 12 June 2013
Received in revised form 9 September 2013
Accepted 19 September 2013
Available online 15 October 2013

Keywords:
Heat and mass transfer analogy
Condensation inside tubes
Noncondensable gases
Heat transfer coefficient
Inclined tubes

ABSTRACT

A theoretical and experimental investigation on steam condensation in presence of noncondensable gases within horizontal and inclined tubes is summarized in the present paper. A simple correlation mainly based on dimensionless numbers was derived and compared with previous formulations based on the diffusion layer model. The noncondensable gases presence during condensation is an important issue affecting the whole thermodynamic efficiency of the process, and for this reason highly investigated by many researchers. The experimental data obtained for condensation, inside horizontal or inclined tube (15°, 30° and 45°) with an internal diameter of 22 mm, of an air/steam mixture, at low mixture Reynolds numbers (<6000), have been used to verify the present heat and mass transfer analogy (HMTA) formulation. In order to perform the heat and mass transfer analogy, the suction effect at the interface has been taken into account since it considerably affects temperature and concentration profiles and hence the transfer coefficients. The model of Chato is used for the condensate boundary layer since it has been identified to be the better model under the experimental condition. Finally, the experimental data have been compared with the theoretical Couette flow model with transpiration showing a quite good agreement.

1. Introduction

Condensation on the cooling surfaces is a phenomenon of great importance in the chemical process and power industries, including nuclear power plants, because it allows to achieve very high heat transfer coefficients, but the presence of noncondensables in steam greatly affects the condensation process.

In a power plant condenser, in order to have a high thermodynamic efficiency, the temperature as low as possible has to be provided at heat rejection or exhaust end of the cycle together with the highest possible vacuum level. Because of the condenser operating pressure is lower than the outer environment, it is possible to have an air entry through small faulty seals (e.g. containers' flanges, connections, pipes, etc.). This causes condenser pressure increase and hence a reduction in the thermodynamic cycle efficiency.

The same performance and efficiency reduction occurs in a thermal desalination condenser unit where, in addition to gases entry from faulty seals, the feed water dissolved gases (i.e. oxygen, nitrogen in low concentrations and carbon dioxide, in much larger concentrations) leave the liquid phase during the water evaporation process. Since in most thermal desalination units the steam that does not condense at a stage, with all the noncondensable gases content, is transferred to another, this causes gases accumulation up to unacceptable concentrations.

In the nuclear industry the effect of noncondensable gases on steam condensation is one of the major safety-related issues: the steam condensation within the containment, in presence of air and possibly hydrogen (produced from exothermic fuel cladding chemical reaction with steam or from the radiolytic decomposition of water), becomes an important phenomenon during LOCA (Loss of Coolant Accident) or steam line break accident. The effect of non-condensable gases on condensation heat transfer is relevant to certain decay heat removal systems in advanced reactor designs, such as passive containment cooling systems.

Additionally, nitrogen gas in accumulators is a source of noncondensable gas, which may affect the condensation heat transfer inside the steam generator tubes of nuclear power plants, and may affect the core make-up tank performance.

The main system related to this phenomenon is the Passive Containment Cooling System (PCCS), which is responsible of the passive decay heat removal from the containment during a long-term cooling period. The containment pressure trend is due both to the PCCS performance and to the amount and temporal distribution of noncondensable gases within the containment compartments (i.e. nitrogen or air initially filling the containment volume and hydrogen released later during the transient from the reactor core).

* Corresponding author. Tel.: +39 06 49918649; fax: +39 06 49918604.
E-mail addresses: gianfranco.caruso@uniroma1.it (G. Caruso), damiano.vitaledimaio@uniroma1.it (D. Vitale Di Maio).
[1] Tel.: +39 06 49918639; fax: +39 06 49918604.

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.049

Nomenclature

A	heat transfer surface
C	total molar concentration
c_p	specific heat at constant pressure
d	tube diameter
D	effective diffusivity
F	correction factor
g	gravity acceleration
h	heat transfer coefficient
k	thermal conductivity
ℓ	coordinate along the tube axis
l	reference length
L	length
M	molecular weight
m''	mass flux
p	pressure
q''	heat flux
$\dot{Q}$	heat transfer rate
r	radius
R	mass transfer driving force
R_0	ideal gas constant
T	temperature
U	overall heat transfer coefficient
w	mass fraction
x	local quality
y	reference direction
Y	mole fraction

Subscripts

0	reference condition
an	analogy
avg	average
b	bulk
c	condensation heat
cond	condensation
corr	correlation
cw	cooling water
exp	experimental
e	external
f	film condensate
g	air/vapor mixture
i	internal
j	condensation-subcooling boundary
I	interface
l	liquid phase
m	mass, mass transfer
mo	mass transfer without suction effect
nc	noncondensable
o	without suction effect
s	sensible heat
ss	stainless steel
sub	subcooling
t	total
v	vapor phase
w	wall

Superscripts

$*$	corrected formulation
in	inlet
lm	logarithmic mean difference
m, n	generic exponent
out	outlet
s	saturation

Greek letters

β_m	suction parameter
δ	thickness
ϕ	molar fraction ratio
Φ	suction factor
Γ	mass flow rate
κ	mass transfer coefficient
λ	latent heat
μ	dynamic viscosity
θ	tube inclination angle
ρ	density
σ	experimental uncertainty
Ω	half stratification angle (Chato's model)

Dimensionless number

Ga	Galileo number
Ja	Jakob number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Sc	Schimdt number
Sh	Sherwood number

Finally the steel containment vessel can provide the heat transfer surface that removes heat from inside the containment and rejects it to the atmosphere, as in the Westinghouse AP-600 and AP-1000 designs. In these nuclear power plants, heat is removed from the containment vessel by continuous natural circulation flow of atmospheric air. During an accident, the air cooling is supplemented by evaporation of water that drains, by gravity, from a tank located on the top of the containment shield building.

In order to allow a suitable design of such a component, a fundamental aspect to be analyzed is the behavior of steam condensation within tubes when noncondensable gases are present. A realistic analysis of the effects of the heat transfer to structures has to cope with many basic difficulties:

- the heat transfer process depends on a large number of parameters (e.g. geometry, material composition, temperature, boundary layer velocity, mixture composition, etc.), which often interact in many complex ways;
- the heat transfer is strongly dependent on the location (e.g. different atmosphere conditions, possible water films, structure properties and orientation, etc.); no proper averaging is possible because most of the effects involved are non-linear;
- the heat transfer process is transient because of the time-dependent behavior of its main boundary conditions (e.g. varying atmosphere properties, non-steady structure heat up, etc.).

A technique commonly used by researchers is to correlate experimental data as a function of noncondensable gases concentration: as heat transfer coefficient or as correction factor of the condensate film resistance in pure steam condensation condition. Experimental data are usually correlated and presented as average heat transfer coefficients or Nusselt numbers.

These correlations are usually functions of such parameters as the Reynolds number, the Prandtl number, the noncondensable mass fraction, etc.; some correlations are reported in [1–7].