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Peculiarities of the transit phase transformation regime for water droplets that are slipping in humid gas

G. Miliauskas [a], M. Maziukienė [a,*], V. Ramanauskas [b]

[a] Kaunas University of Technology, Studentų g. 56, Kaunas LT-44239, Lithuania
[b] UAB "Enerstena", Raktazolių 21, Kaunas LT-52181, Lithuania

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ABSTRACT

Water droplets phase transformation cycle in humid gas is defined by time moments of droplets generation and evaporation. Transit and equilibrium evaporation regimes are provided. An exclusive attention is payed for droplet heat and mass transfer processes analysis in transit phase transformation regime when providing condensing and transit evaporation regimes in it. Specific transfer processes regularities were highlighted for each droplet phase transformation regime and original their interpretation according to droplet thermal and energy state variation is presented. Droplet slipping in gas impact for its phase transformation cycle is evaluated. Essential impact of rising water circulation at the droplet slipping in gas for condensation phase transformation regime duration that affects boundary conditions of droplet evaporation regime and transfer processes interaction in it was based on.

1. Introduction

Water in dispersible form is important in natural phenomena and is widely applicable in practice. The water droplet heat and mass transfer at humid atmospheric air is taken into account when assessing atmospheric appearance and creating climate models [1]. Water spray application in air conditioning [2], fire suppression [3–7], gas cooling [8,9] and agricultural irrigation systems [10,11] can be considered as traditional. Heat and mass transfer processes are applied for surface treatment [12–14] and protection [15–18], cooling towers [19–21,9,22], washing processes [23–25], water freezing and crystallization [26–28], aerosols [29,30], gas turbines [31–35], heat recovery from humid flue gas [36,37], NO_x reduction in fuel combustion [38–40], water and fuel emulsions [41–44], plasma technique [45–47] and other thermal technologies. Wide water spraying application practice defines a variety of boundary conditions for droplet heat and mass transfer and abundance of factors influencing transfer processes rate. For their assessment a systemic approach to technologies based on by water spraying is important. The droplet link makes preconditions to provide a consistent phase transformations potential change on the droplet surface and provided summarize it by droplet phase transformation cycle $\tau \equiv 0 \div \tau_f$ [48]. The beginning of the cycle is defined by droplet appearance moment $\tau \equiv 0$, while the end of cycle refers droplet evaporation moment $\tau \equiv \tau_f$. Droplet phase transformation cycle of pure water consists from transit (also known as unsteady phase transformation regime) and equilibrium evaporation regimes, when $\tau \equiv 0 \div \tau_{uf}$ and $\tau \equiv \tau_{uf} \div \tau_f$, respectively. Phase transformations regimes are defined according to phase transformation peculiarities that ongoing on the surface of a droplet. The transit phase transformation regime combines condensing $\tau \equiv 0 \div \tau_{co}$ and transit to equilibrium evaporation $\tau \equiv \tau_{co} \div \tau_{uf}$ regimes. For condensing phase transformation regime proceeding spraying water temperature $T_{l,0}$ ought to be lower than the dew point temperature T_{dp}. A droplet surface warming to dew point temperature unambiguously defines the end of condensing regime: $\tau_{co} \equiv \tau$, when $T_R(\tau = \tau_{co}) = T_{dp}$. In the transit evaporation regime droplet warms to equilibrium evaporation temperature T_{ee}. Equilibrium evaporation is considered as phase transformation case ongoing on the droplet surface, when all energy supplied for droplet evaporates water. Gas flow temperature and humidity as well as droplet heat transfer conditions are defined by the temperature T_{ee} [49]. To the thermal state T_{ee} the heating droplet approaching asymptotically. Therefore to define the equilibrium evaporation beginning $\tau \equiv \tau_{ee}$, a complex droplet thermal and energy state analysis or additional conditions providence are necessary.

At technologies based on by liquid spraying an influence of droplet phase transformation cycle regimes is different. Where sprayed liquid evaporation is necessary (liquid fuel combustion, flash gas cooling, superheated vapor parameters regulation etc.) a

* Corresponding author.
E-mail address: monika.maziukiene@ktu.lt (M. Maziukienė).

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Nomenclature

a	thermal diffusivity, m^2/s
B_T	Spalding heat transfer parameter
B_M	Spalding mass transfer parameter
c_p	mass specific heat, J/(kg K)
C_F	friction drag coefficient
C_l	full drag coefficient
D	mass diffusivity, m^2/s
Fo	Fourier number
k_c^-	effective conductivity parameter
m	mass flux density, kg/(m^2 s)
M	mass, kg
L	latent heat of evaporation, J/kg
n	number of the term in infinite sum
Nu	Nusslet number
p	pressure, Pa
Pe	Peclet number
Pr	Prandtl number
q	heat flux density, W/m^2
r	radial coordinate of a droplet, m
R	Radius of a droplet, m
Re	Reynolds number
R_μ	universal gas constant, J/(kmol K)
T	temperature, K
V	Volume, m^3
δ	relative error of calculation,
δ_{leg}	legale relative error of calculation,
η	non-dimensional radial coordinate, m
λ	thermal conductivity, W/(m K)
μ	molecular mass, kg/kmol
ρ	density, kg/m^3
τ	time, s
w	velocity, m/s
Δw_l	droplet slipping velocity in gas, m/s

Subscripts

c	convection
co	vapor condensation regime
e	evaporation
ee	equilibrium evaporation regime
eu	transit evaporation regime
f	droplet phase transformations regime
g	gas
i	time index in a digital schemes
it	index of iteration
I	index of control time
IT	index of finale iteration
j	index of droplet cross-section
J	index of droplet surface
k	conduction
co	vapor condensation regime
l	liquid
m	mass average
R	droplet surface
r	radiation
s	saturation state
dp	dew point
uf	droplet transit phase transformations regime
v	vapor
vg	vapor–gas mixture
Σ	total
0	initial state
∞	far from a droplet
$*$	variable

Superscripts

+	external side of a droplet surface
–	internal side of a droplet surface

Abbreviations

"k"	heating by conduction;
"$k+r$"	combine heating by conduction and radiation
"c"	heating by convection
"$c+r$"	combine heating by convection and radiation
P	parameter of droplet heat and mass transfer
$\bar{P}$	dimensionless parameter of droplet heat and mass transfer

regime of droplet equilibrium evaporation usually becomes the most important. For air-conditioning the condensation and evaporation regimes are relevant, however water droplets are not completely evaporated. Technologies of water spraying in heat utilization from humid biofuel flue gas demands a specific approach to droplet phase transformation cycle. A contact type condensing economizers are based on by water spray to humid flue gas or phase transformation heat utilization during process of water vapor condensation on droplets surface. In this case droplets surface temperature control is relevant, in order to ensure a condition $T_R(\tau) < T_{dp}$ that is necessary for condensation process proceeding. At recuperative type condensing economizers phase transformations heat from humid flue gas is utilized when they flow through non-ferrous metal tubes. In this case, the water vapor condensates on the gravity film surface, where for hydrodynamics improvement water is sprayed at the upper part in economizer. To define flue gas temperature and humidity that flows inside tubes it is important to take into account a partial evaporation on their way till contact with tube fiber. Therefore, in condensing economizer technologies, as well as in air conditioning, knowledge of condensation and evaporation regime is important. However, at condensing economizer technologies a special attention is needed for potential self-variation of phase transformation regime from condensation to evaporation. It is undesirable, because at the process of droplet or water film evaporation flue gas could be irrigated again and heat recovery efficiency would be reduced.

Contact surface area between sprayed liquid droplets and their carrying gas flow is highly developed, therefore heat and mass transfer is effective. It is accompanied by interplay interaction of the combine transfer processes. In interaction important factors are Stefan hydrodynamic flow that accompanying droplets heat transfer and phase transformations, selective radiation absorption in semi-transparent droplets and their slipping in gas. Stefan hydrodynamic flow increases droplets diffusion evaporation and suppress droplet convection heating [50,51]. Radiation flux that is absorbed by droplet volume influence droplet thermal state [4,52–55] and can even cause temperature field gradient vector changes. The droplet slipping into gas makes preconditions to raising a forced liquid circulation and to intensify heat transfer processes in it.

This article analyses regularities of water droplets phase transformations cycle in humid gas. Exclusive attention is given for variation of phase transformation regime and influence of slipping droplet heat transfer.