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Irreversibility analysis of falling film absorption over a cooled horizontal tube

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ABSTRACT

Based on a numerical study of the water vapour absorption process in LiBr–H_2O solution, for a laminar, gravity driven, viscous, incompressible liquid film, flowing over a horizontal cooled tube, irreversibilities related to fluid friction, heat transfer, mass transfer and their coupling effects have been locally and globally examined. The hydrodynamic description is based on Nusselt boundary layer assumptions. The tangential and normal velocity components, respectively obtained from momentum and continuity equations, have been used for the numerical solution of mass and energy transport equations in the two-dimensional domain defined by the film thickness and the position along the tube surface. Local entropy generation calculation can be performed referring to the calculated velocity, temperature and concentration fields. Results have been explored in different operative conditions, in order to examine comprehensively the impact of the various irreversibility sources and to identify the least irreversible solution mass flow-rate for the absorber. As a parallel, a refined understanding of the absorption process can be obtained. Considering absorption at the film interface and cooling effect at the tube wall, the analysis thermodynamically characterises the absorption process which occurs inside actual falling film heat exchangers and establishes a criterion for their thermodynamic optimisation. Results suggest the importance to operate at reduced mass flow rates with a thin uniform film. Meanwhile, tension-active additives are required to realise this condition.

1. Introduction

All the real processes occurring in an energy conversion system are associated to an unavoidable degradation of the original amount of energy. The second law of thermodynamics provides a qualitative description of physical processes and is critical to identify their limitations. Namely, according to this general design issue, thermal design and basic thermodynamics are to be employed together with the purpose of identifying the optimum size or operating regime of a certain engineering system, where by "optimum" the least exergy destroying condition, which can still assure the fundamental engineering function, is intended.

Devices in which simultaneous heat and mass exchanges occur are commonly used in the power and refrigeration industries, as well as air conditioning where both temperature and humidity might be simultaneously controlled. This devices are also part of absorption machines as generator and absorber. The use of the vapour absorption cycle for heat driven energy systems was among the first popular and widely used methods of refrigeration. Even though the development of vapour compression cycles has limited the implementation field of vapour absorption systems, the main benefits of absorption cycle are still evident: since a negligible amount of electricity is needed, waste heat can be used as the main energy source, and higher reliability can be ascribed to the absence of moving parts. In addition, typically used refrigerants (water or ammonia) are not responsible of ozone depletion effect. The fundamental heat and mass transfer processes constituting the absorption cycle are realised inside specific heat exchangers, whose characteristics have decisive effects on the overall system efficiency, on its dimensions and its cost. In the conventional case of falling film heat exchangers high transfer coefficient and low pressure drop can be obtained. However, the attempt to experimentally and theoretically describe the complex heat and mass transfer mechanism occurring inside these devices is still incomplete and has not led to conclusive approaches. In terms of modelling efforts, [1–5] presented simplified models for falling film absorption of water vapour over a horizontal tube. Similarly, they solved the problem with a finite difference method and studied the effect of different parameters on the coupled heat and mass transfer processes. Among the possible scenarios, entropy generation minimisation has been widely accepted as a method for heat

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Nomenclature

a	thermal diffusivity [m^2s^{-1}]
C	molar concentration [$mol{\cdot}m^{-3}$]
c_p	isobaric molar heat [$J{\cdot}mol^{-1}K^{-1}$]
D	mass diffusivity [m^2s^{-1}]
E	Entropy generation rate per tube unit length [$W{\cdot}m^{-1}K^{-1}$]
g	gravity [$m{\cdot}s^{-2}$]
G	mass flux per unit surface [$kg{\cdot}m^{-2}s^{-1}$]
h	molar enthalpy [$J{\cdot}mol^{-1}$]
H	number of nodes in radial direction
j	molar flux [$mol{\cdot}m^{-2}s^{-1}$]
k	thermal conductivity [$W{\cdot}m^{-1}K^{-1}$]
M	molar weight [$kg{\cdot}mol^{-1}$]
N	number of nodes in tangential direction
P	pressure [kPa]
q	heat flux per tube unit length [$kW{\cdot}m^{-1}$]
r	outer tube radius [m]
R	grid ratio in normal direction
Re	Reynolds Number
S	volumetric entropy generation rate [$W{\cdot}m^{-3}K^{-1}$]
s	molar entropy [$J{\cdot}mol^{-1}K^{-1}$]
T	temperature [K]
u	streamwise velocity [$m{\cdot}s^{-1}$]
v	radial velocity [$m{\cdot}s^{-1}$]
V	total velocity [$m{\cdot}s^{-1}$]
x	local tangential position [m]
y	local normal position [m]

Greek symbols

β	streamwise Angle [rad]
ε	dimensionless tangential position
φ	general parameter identification
η	dimensionless normal position
τ	shear stress tensor [Pa]
Γ	mass flow rate per unit length [$kg{\cdot}s^{-1}m^{-1}$]
δ	film Thickness [m]
μ	viscosity [$Pa{\cdot}s$]
ρ	density [$kg{\cdot}m^{-3}$]
γ	chemical potential [$J{\cdot}mol^{-1}$]
ω	LiBr mass concentration

Subscripts

0	standard
abs	absorption
c	convection
d	diffusion
e	equilibrium
f	friction
G	global
H_2O	water
i, j	node indexes
if	interface
in	inlet
min	minimum
S	solution
sat	phases equilibrium
t	thermal
v	vapour
w	wall

exchangers' design. Entropy can be used to evaluate the irreversibility introduced, characterise the quality of energy-conversion, and eventually, develop consistent criteria for the optimisation and control of a component or the system. The existence of thermal, velocity and concentration gradients in the computational field representing the absorptive film yields a non-equilibrium state, responsible of entropy generation (better defined as entropy variation due to irreversibility).

To the authors' knowledge, few researchers [6–9] have previously carried out second law analyses of heat and mass exchange devices. In particular, [10,11] report a second law-based analytical study for gas absorption into a laminar, falling, viscous, incompressible, liquid film. The main conclusion states that entropy generation is mainly ruled by the coupling effects between heat and mass transfer near the gas–liquid interface and by the viscous irreversibility when approaching the solid wall. However, heat transfer at the wall has not been included in the problem. Simultaneous cooling and absorption allow the process to be maintained far from the thermodynamic equilibrium at which absorption will not occur.

The main purpose of this work is to perform a numerical and parametric analysis of the volumetric entropy generation rate inside the computational domain representing real LiBr–H_2O absorptive films, where energy and species transport equations are solved numerically. Results can be used to reduce irreversibility in a falling film heat exchanger, in order to optimise the absorption process both locally and globally.

2. Model description and numerical solution

The system in question is showed schematically in Fig. 1. A single horizontal tube is considered and the LiBr–H_2O solution flows viscously down over it driven by gravity as a laminar incompressible liquid, while vapour mass transfer process occurs at the interface of the flowing film. The heat released by the absorption is rejected to the cooling water flowing inside the tube. Heat and mass transfer characteristics have been studied by solving numerically transport of mass and energy equations, under the following main assumptions:

1. The flow is steady, laminar and without interfacial waves.
2. Thermodynamic equilibrium exists at the film interface with the vapour.
3. There is no shear force between the liquid film and the vapour.
4. Disturbance at the edges of the system are neglected assuming that both the tube circumference and length are large comparing to the film thickness.
5. Physical properties are function of the inlet concentration and temperature, but remain constant while flowing on the single tube.
6. Heat transfer to vapour phase is negligible.
7. Outside tube surface temperature is constant and equal to the coolant temperature.
8. Body fitted coordinates (x along the tube surface and y normal to it at any point) are used because the film thickness is small if compared to the tube circumference [5].

The hydrodynamic description is based on Nusselt boundary layer assumptions. The tangential and normal velocity components (respectively, Eqs. (1) and (2)), from continuity and momentum equations, have been used for solving numerically the transport of mass and energy (respectively, Eqs. (4) and (3)).