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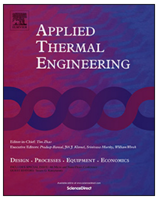

Research Paper

Entropy parameters for falling film absorber optimization

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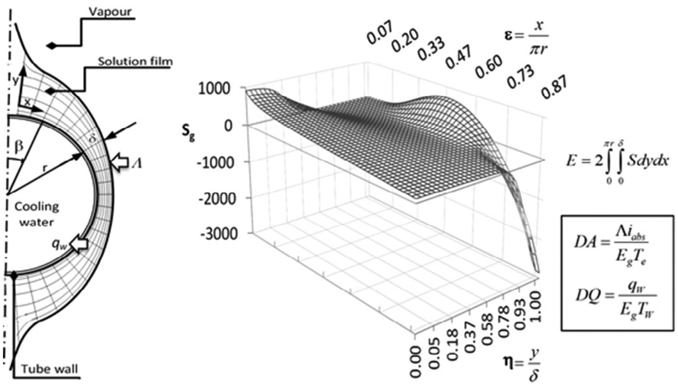
HIGHLIGHTS

- Local entropy generation analysis of an absorptive film on a cooled horizontal tube.
- Parametric study of the entropy generation related to various irreversibility sources.
- Identification of the least irreversible solution mass flow-rate.
- Parameters accounting for the irreversibility are used as optimization criterion.

GRAPHICAL ABSTRACT



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ABSTRACT

A local entropy generation analysis, for water vapor absorption in LiBr-H_2O solution, is performed referring to velocity, temperature and concentration fields obtained from the numerical solution of mass and energy transport equations. The hydrodynamic description is based on Nusselt boundary layer assumption and the actual amount of irreversibility introduced is determined for an absorptive falling film over a cooled horizontal tube inside the absorber. Results are explored in different operative conditions in order to examine the impact of the various irreversibility sources in a wide operative range. A least irreversible solution mass flow-rate can always be identified. Furthermore, a simple and general thermodynamic analysis, carried out regarding a refrigerating and a heat boosting applications, makes evidence of a dimensionless group "Q/σT" that separates the weight of the irreversibilities and gives the way to an optimization criterion applied to the absorber in order to improve the whole system efficiency. Both thermodynamic equilibrium and sub-cooling conditions of the solution at the inlet are considered for typical temperature and concentration of refrigerators' absorbers and heat transformers' absorbers. Results suggest the importance to work at reduced mass flow-rates with a thin uniform film. In practice, tension-active additives are required to realize this condition. Also, it is highlighted that the two parameters defined with reference to the dimensionless group "Q/σT" can be maximized by specific values of the tube radius, operative Reynolds number, solution sub-cooling and temperature difference between the wall and the inlet solution.

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1. Introduction

Nowadays the awareness of the environmental issues of the planet steers toward clean and efficient energy conversion systems. Absorption chillers, heat pumps and heat transformers represent an opportunity in this direction. In fact, the use of the vapor absorption represents one of the first widely used methods of refrigeration. Although the development of vapor compression cycles has limited the implementation field of vapor absorption systems, the main benefits of the absorption cycle are still obvious and of renewed importance: firstly, since a negligible amount of electricity is required exclusively for the solution pump, waste heat can be used as the main energy source and higher reliability can be ascribed to the reduced number of moving parts. Accordingly, absorption plants demonstrate long lifetimes and excellent part-load operability. In addition, typically used refrigerant (water or ammonia) are not responsible for ozone depletion effect.

All the real processes arising as part of an energy conversion system are associated with an unavoidable degradation of the earliest amount of energy. The second law of thermodynamics provides a qualitative description, which is not confined to engineering, and is critical to identify the limitations imposed to a physical process. The purpose of thermodynamic optimization methods deals with recognizing features and physical circumstances by which the system fulfils its roles while performing at the highest thermodynamic level possible. Among the possible scenarios, the method of entropy generation minimization can be used to characterize the quality of energy-conversion and develop consistent criteria for the optimization and control of the system after the irreversibilities introduced have been properly evaluated. 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, topology or operating regime of a certain engineering system. From this point of view, the achieved technological progress could be interpreted as a secondary result of entropy generation minimization [1].

From the prospective of the global system, authors in References 2 and 3 have presented a literature review of finite-time thermodynamics optimization of absorption refrigeration systems and analyzed the various possible objective functions. In general, in order to consider the temperature level of the various heat fluxes involved in the energy conversion process, a second law approach is particularly significant for the characterization of the performance of heat-driven systems. Exergy-based analyses of water-lithium bromide absorption refrigeration systems, in both their single [4] and multiple effect configurations [5], and absorption heat transformers [6], have been performed to evaluate performance and exergy loss of the system and its components. As a rule, some studies [4–7] have highlighted that the maximum exergy destruction occurs in the absorber and the analysis and optimization of this device are crucial for the absorption system in refrigerator and heat transformer applications. In the conventional case of falling film heat exchangers, high transfer coefficient and low pressure drop can be obtained. However, the attempt to comprehensively describe and measure the complex heat and mass-transfer mechanism occurring inside these devices is still incomplete and has not led to conclusive approaches. This work focuses on the details of falling film absorption; however, local details are believed to play a major role on the global performance of the process and might have leading impact on the plant operability. Under this standpoint, local results are to be summed up to a higher scale, and used globally to optimize transfer performance of the absorber, its design and operational regime with reference to the final duty of the system.

In terms of modelling efforts, some studies [8–12] have discussed simplified models for falling film absorption of water vapor 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.

To the authors' knowledge, a few studies [1,13–15] performing a second law analysis of absorption devices have been previously carried out. In particular, Chermiti et al. [16] and Hidouri et al. [17] report a second law-based analytical study for gas absorption into a laminar, gravity-driven, viscous, incompressible, isothermal liquid film. The main conclusion states that entropy generation is mainly ruled by the coupling effects between heat and mass transfer in proximity of the gas–liquid interface and by viscous irreversibility near the solid wall. However, heat transfer and the tube wall geometry have not been included in the problem. Simultaneous cooling and absorption allow the process to be maintained far from the thermodynamic equilibrium at which absorption would not occur any longer.

The main purposes of this work stem from the proper expression of the local entropy generation rate representing real LiBr-H_2O absorptive films.

Since entropy generation minimization has been widely accepted as a method for heat exchangers' design and optimization [18–24], a local analysis and a parametric study are carried out by means of the numerical solution of energy and species transport equations around a cooled horizontal tube. Finally, a simple thermodynamic analysis shows that the absorption system performance can be improved by means of the optimization of the absorber design and operational regime when suitable dimensionless groups, accounting for the total entropy generation introduced, are defined as objective parameters.

2. Model description and numerical solution

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 vapor mass transfer process occurs at the film interface. The heat released by the absorption is rejected to the cooling water flowing inside the tube. The system under analysis is schematically shown in Fig. 1. Heat and mass transfer characteristics of the absorber tube are obtained by numerically solving the species and energy transport equations (respectively, eqs. 4 and 3) under the following main assumptions:

- Steady and laminar flow without interfacial waves.
- Thermodynamic equilibrium with the vapor at the film interface.
- Negligible shear force between the liquid film and the vapor.
- Disturbance at the edges of the system are neglected and body fitted coordinates (x along the tube surface and y in the radial direction) are used assuming that both the tube circumference and length are large if compared to the film thickness [12].
- Physical properties are constant and calculated with reference to the inlet values of concentration and temperature.
- Negligible heat transfer to the vapor phase.
- Constant temperature of tube surface.

Tangential and normal velocity components (respectively, eqs. 1 and 2) from continuity and momentum equations (based on Nusselt integral solution) are employed.

$$u=\frac{\rho g}{\mu}\sin\beta\left(\delta y-\frac{1}{2}y^2\right) \tag{1}$$

$$v=-\frac{\rho g y^2}{2\mu}\left[\frac{d\delta}{dx}\sin\beta+\frac{1}{r}\left(\delta-\frac{y}{3}\right)\cos\beta\right] \tag{2}$$