Graduate School of Fundamental Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Thermo-fluid dynamics of falling film type vapour absorption process

流下液膜式冷媒吸収プロセスの熱流体力学的挙動
に関する研究

申 請 者
(Applicant Name)

NICCOLO	GIANNETTI
ジャンネッティ	ニコロ

Department of Applied Mechanics, Research on Dynamics and Control of Mechanical Systems

February, 2016

Absorption represents an opportunity towards clean and efficient energy conversion systems. However, the attempt to characterise heat and mass transfer performance of those devices that make use of this process is still inadequate and has not led to conclusive approaches. On the other hand, the recent technical development of absorption chillers, heat pumps and heat transformers pushes towards increasingly complex plant configurations, and, in fact, seems to stand a step forward with respect to the theoretical background needed for an accurate prediction, optimisation and control of the performance of these systems.

This work arises from the awareness of this discrepancy and constitutes an effort to get closer to a generalised method for absorption systems modelling and optimisation.

The structure of this thesis reflects a convergent approach, originating from the development of a general model representing the thermodynamic silhouette of these systems in their interactions with the outer environment. The global system performance constitutes, in fact, the starting point as well as the final target to be addressed. In a preliminary chapter, absorption systems are considered as rather indefinite multi-temperature-level thermodynamic entities, focusing on their similarities regardless their technical differences. A large spectrum thermodynamic analysis provides general guidelines for the system optimisation that suggests referential directions towards which orientate research efforts. The combination of first and second principle of thermodynamics extend the potentiality of the model, by providing a qualitative description which identifies performance limitations, suggests how to improve system COP and that can be used to perform existing plant diagnostic. Suitable dimensionless parameters for an overall optimisation are introduced and their influence on the cycle efficiency is investigated. Dependence on the main factors is highlighted in a way that shows how to change them in order to improve the overall efficiency, pointing out the importance properly designed components and in particular of the absorber. This approach defines a general thermodynamic criterion for the characterisation of three-thermal irreversible systems, exemplified for absorption chiller and heat transformer application cases showing the leading importance of optimised absorbers.

Taking advantage of the understanding gained from this general analysis, a detailed numerical model of falling film absorbers is presented and used as the basis for a thermodynamic optimisation of the component by targeting the ultimate duty of the system. Also at this investigation level, absorption chiller and heat transformer application cases should be distinguished and treated independently. Precisely, chapter 3 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 point of view, local results are summed up to a higher scale, and used globally to optimise transfer performance of the absorber, its design and operational regime with reference to the final goal of the system. Among the possible scenarios, entropy generation minimisation can be used to characterise the quality of energy-conversion processes, and develop consistent criteria for the design, optimisation and control of the whole system. Besides, entropy constitutes a critical variable especially when the scale of the analysis is contracted to the order at which macroscopic and microscopic physics come to a shared limit of validity. This not yet resolved threshold is close enough to the scale of the processes involved in transport phenomena in general, and absorption in particular.

From this standpoint, a local numerical analysis of the absorption entropy generation is used as the basis to define suitable dimensionless objective parameters for the improvement of the whole system performance by means of the optimisation of the absorber. Results suggest the importance to work at reduced mass flowrates with a thin uniform film to increase the system performance and/or reduce its size.

At these operative conditions, specifically at low Reynolds numbers, the assumptions of a film with uniform thickness and complete wetting of the transfer surface can't be considered even approximately rigorous, and leads to an unacceptable inaccuracy of simulations results in that region (the obtained trend itself disagrees with measurements). Furthermore, partial wetting is recognised to occur even at typical system operative conditions. Accordingly, the inadequacy of the available models of the absorptions process in falling film heat exchangers can be ascribed to a major issue correlated to this particular phenomenon. The chaotic behaviour characterising falling film dynamics even at low Reynolds number constitutes a fascinating phenomenon frequently occurring in nature and being recurrent in technical applications. As a rule, these devices require conditions which avoid thin liquid films to break into a series of rivulets, leaving the solid heat transfer surface partly uncovered and/or lowering the extension of the liquid-vapour interface, where mass transfer occurs. Both a criterion of film stability to identify the minimum wetting rate able to ensure a complete wetting and, after the film breakage, a method to estimate the wet part of the surface are demanded for an accurate description of these processes. Unfortunately, there is not a general agreement on the precise mechanism of film break-down and data on a variety of parameters such as surface inclination, mode of liquid distribution, temperature level, physical properties, etc., which may have an important effect on maintaining fully wetted surfaces, are incomplete. Nevertheless, the role of the film wetting ability in determining the efficiency of the absorption process has been recognised as a critical factor. Considering the main features and the characteristic scale of falling film absorption, the influences of inertia (in the specific case of interest, directly caused by gravity) and surface tension result to be dominant on the film hydrodynamic behaviour. In particular, once the solid surface geometry is defined, their conflicting effects (gravity forcing towards flowing configurations and iso-potential flat interfaces, whereas surface tension tends to create stationary spherical phase boundaries) establish configuration-stability limitations which, in certain operative conditions, define metastable hysteresis phenomena. Therefore, the stability of a uniform film is reduced to the identification of an energetically stable configuration characterised by a minimum of its mechanical energy (including kinetic and surface tension energy) and the definition of a concurrent broken rivulet configuration can be used to describe the liquid partial wetting behaviour. This forth chapter re-establishes an energy based criterion for the film stability for a generic inclination of the solid surface, consistently with a composed cross-section shape of the rivulet, which introduces an additional geometrical degree of freedom to the problem. Accordingly, the width of the surface can be used as a parameter. Moreover, this work aims also at the local characterisation of the transition from uniform film to the steady rivulet configuration by applying a Lagrangian approach to describe the local trajectory of the fluid particle at the edge of the rivulet. This approach is extended to include hysteresis behaviour of the fluid wettability and the contact angle when increasing or decreasing mass flowrates are delivered. An application case on a vertical fin-tube contactor is studied and compared with experiments for a first validation.

Afterwards, a semi-empirical model suitable for a horizontal tube bundle is developed to match the characteristics of real absorbers. In this way, the effect of these phenomena can be included in the absorption model to extend its validity and increase its accuracy. The effects of different parameters is analysed to clarify the model ability to describe different phenomena in detail.

On one side, numerical analysis and CFD have a great potential and could be very accurate if the problem is formulated properly. However, the time required to reach an accurate solution and the fact that its validity is restricted to the specific case, the operative and boundary conditions specifically selected should be well-thought-out. These specific solutions cannot be directly generalised and don't provide general guidelines. Under this point of view, to extend the validity of the modelling effort and capture the physics of the problem, analytical solutions still maintain their fundamental importance. Hence, as a closing modelling effort, this chapter articulates, slims down and canalises the understanding developed in the previous chapters in a detailed, widely applicable and time-saving method to predict heat and mass transfer characteristics of horizontal-tube falling film absorbers. In particular, as demonstrated so far, a two-dimensional model is able to capture the physics of the phenomenon. The solution considers the horizontal tube cylindrical geometry. Also, by means of the inclusion of a film stability criterion and a linear wetting model, partial wetting phenomena are incorporated in the analysis, thus extending the target range of the resulting heat and mass transfer coefficients expressions and, in parallel, increasing their accuracy. A first comparison with the numerical solution is presented and used as a reference to test the validity of the simplifying assumptions introduced.

Finally, experiments and data collections are performed as a closing point to validate the theoretical absorption model in a wide range of operative conditions.

Lastly, the eighth chapter is intended to summarise the results obtained in order to draw significant conclusions and future prospects.

早稲田大学　博士（工学）学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

氏 名　Niccolo Giannetti　　　　　　　　　印

（As of 2 月, 2016）

種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
論文 1	Thermodynamic analysis of regenerated air-cycle refrigeration in high and low pressure configuration, International Journal of Refrigeration, vol. 40 (2014), 97-110, N. Giannetti, A. Milazzo.
2	Entropy parameters for desiccant wheel design, Applied Thermal Engineering, vol. 75 (2015), 826-838, N. Giannetti, A. Rocchetti, K. Saito, S. Yamaguchi.
③	Irreversibility analysis of falling film absorption over a cooled horizontal tube, International Journal of Heat and Mass Transfer, vol. 88 (2015), 755-765, N. Giannetti, A. Rocchetti, K. Saito, S. Yamaguchi.
④	Entropy parameters for falling film absorber optimization, Applied Thermal Engineering, vol. 93 (2016), 750-762, N. Giannetti, A. Rocchetti, A. Lubis, K. Saito, S. Yamaguchi.
⑤	Thermodynamic optimization of three-thermal irreversible systems, International Journal of Heat and Technology, vol. 34, (2016) Special Issue 1, S83-S90, N. Giannetti, A. Rocchetti, K. Saito.
国際発表 ⑥	Analytical study of falling film absorption on a partially wetted horizontal tube, 26th International Symposium on Transport Phenomena, September 27th - October 1st (2015) Leoben (Austria), N. Giannetti, K. Saito, S. Yamaguchi, A. Rocchetti.
⑦	Local entropy generation analysis of water vapour absorption in a LiBr-H_2O solution film, over a horizontal cooled tube, 24th IIR International Congress of Refrigeration, August 16th – 22nd (2015) Yokohama (Japan), N. Giannetti, A. Rocchetti, K. Saito, S. Yamaguchi.
8	Cascade refrigeration system with inverse Bryton cycle on the cold side, 24th IIR International Congress of Refrigeration, August 16th – 22nd (2015) Yokohama (Japan), N. Giannetti, A. Milazzo, A. Rocchetti.
⑨	Thermodynamic optimization of three-thermal irreversible systems, CLC2015 Constructal Law & Second Law Conference, May 18th - 19th (2015) Parma (Italy), N. Giannetti, A. Rocchetti, K. Saito.
発表 ⑩	吸収器の水平管流下膜構成における熱と物質移動係数の解析式 (Analytical expression of heat and mass transfer coefficients on a partially wetted horizontal tube of falling film absorber), 2015 年度日本冷凍空調学会 年次大会, October 20th -23rd (2015), ジャンネッティ ニコロ, 齋藤 潔, 山口 誠一, アンデレア　ロッケッティ.
⑪	Anew model for partial wetting of inclined surfaces, 第 49 回空気調和・冷凍連合講演会講演論文集 (東京海洋大学, 東京), April 15th – 17th (2015), ジャンネッティ ニコロ, 齋藤　潔, 山口 誠一.

早稲田大学　博士（工学）学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

種 類 別 By Type	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
⑫	濡れ性を考慮した水平流下液膜式熱交換器の熱物質移動特性(Heat and mass transfer characteristics of falling film on a partially-wetted horizontal tube), 2014年度日本冷凍空調学会年次大会(佐賀大学, 佐賀), September 10th – 13th (2014), ジャンネッティ ニコロ, 中西 祐一, 山口 誠一, 齋藤 潔.
⑬	Semi-theoretical wettability model for falling film heat exchangers, 第48回空気調和・冷凍連合講演会講演論文集 (東京海洋大学, 東京), April 16th – 18th (2014), ジャンネッティ ニコロ, 齋藤　潔.
記事 ⑭	リキッドデシカント空調システム用中間冷却／加熱型接触器における流下液膜流動状態の可視化 (Visualization of Falling Film on Outer Surface of Fin-Tube Heat Exchanger),「冷凍」10月号第90巻第1056号 (2015), 小林　祐太，ジャンネッティ ニコロ，山口　誠一，齋藤　潔，中山　浩，宮岡　洋一.