UNIVERSIDAD DE SONORA
DIVISIÓN DE INGENIERÍA
POSGRADO EN CIENCIAS DE LA INGENIERÍA

ESTUDIO TEÓRICO-EXPERIMENTAL DE LA GENERACIÓN DIRECTA DE VAPOR EN EL RECEPTOR DE UN SISTEMA TERMOSOLAR DE TORRE CENTRAL

TITULACIÓN POR ARTÍCULOS CIENTÍFICOS PUBLICADOS

QUE PARA OBTENER EL GRADO DE:

Doctor en Ciencias de la Ingeniería

PRESENTA:

M.C. Víctor Manuel Maytorena Soria

HERMOSILLO, SONORA **MARZO DE 2020**


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de la tesis presentada por:

Víctor Manuel Maytorena Soria

Esta tesis ha sido revisada por cada uno de los miembros del Jurado y por mayoría de votos la han encontrado satisfactoria.

26/02/20 Fecha	Jesús Fernando Hinojosa Palafox
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Posgrado en Ciencias de la Ingeniería: Ingeniería Química

AUTORIZACION DEL EXAMEN DE GRADO

25 de Febrero de 2020.

Por la presente se hace constar que el estudiante **Victor Manuel Maytorena Soria,** ha cumplido satisfactoriamente con los requisitos académicos correspondientes para la realización del Examen de grado del programa de Doctorado en Ciencias de la Ingeniería.

Abraham Rogelio Martín García

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COORDINADOR

POSGRADO EN CIENCIAS DE LA INGENIERÍA

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UNIVERSIDAD DE SONORA
División de Ingeniería

Posgrado en Ciencias de la Ingeniería: Ingeniería Química

13 de enero del 2020

M.C. Victor Manuel Maytorena Soria
Estudiante del Doctorado en Ciencias de la Ingeniería
Presente.-

Por medio de la presente le comunico que en sesión de la Comisión Académica del Posgrado en Ciencias de la Ingeniería: Ingeniería Química con fecha 26 de abril del 2019, se aprobó su solicitud de aplicación del Acuerdo de Colegio Académico 06-137/2015 para estudiantes del Doctorado en Ciencias de la Ingeniería: Ingeniería Química. Dicho acuerdo establece que para estudiantes que cuenten con al menos dos artículos publicados y/o aceptado dentro de los 8 semestres de duración del programa, podrán titularse mediante un esquema alternativo al tradicional, en donde el estudiante tendrá la opción de presentar los artículos como su documento escrito que deberá defenderse en la fase oral del examen de grado.

Lo anterior debido a que presentó ante la Comisión Académica del Posgrado evidencia de la publicación de los siguientes artículos en revistas indexadas con resultados relacionados con su Tesis Doctoral:

1. **A. Piña-Ortiz, J.F. Hinojosa, R.A. Pérez-Enciso, V.M. Maytorena, R.A. Calleja, C.A. Estrada**, Thermal analysis of a finned receiver for a central tower solar system, Renewable Energy, vol. 131C, pp. 1002-1012. doi: 10.1016/j.renene.2018.07.123. 2019.
2. **V.M. Maytorena, J.F. Hinojosa**, Computational modeling of direct steam generation in pipes receiving concentrated solar radiation, Ingeniería Mecánica: Tecnología y Desarrollo, vol. 6, No. 3, pp. 107-121, 2018.
3. **V.M. Maytorena, J.F. Hinojosa**, Effect of non-uniform concentrated solar flux on direct steam generation in vertical pipes of solar tower receivers, Solar Energy, vol. 183, pp. 665-676, 2019. doi: 10.1016/j.solener.2019.09.020.
4. **V.M. Maytorena, J.F. Hinojosa**, Three-dimensional numerical study of direct steam generation in vertical tubes receiving concentrated solar radiation, International Journal of Heat and Mass Transfer, vol. 137, pp. 413-439, 2019. doi: 10.1016/j.ijheatmasstransfer.2019.03.101.

Atentamente

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RELATORÍA

A continuación, se presenta una descripción de los artículos publicados durante el estudio doctoral titulado "Estudio teórico-experimental de la generación directa de vapor en el receptor de un sistema termosolar de torre central", para llevar a cabo la obtención del grado de Doctor con la opción de publicación de artículos como alternativa para la fase escrita del examen de grado.

El objetivo general de este trabajo fue "Estudiar teórica y experimentalmente la generación directa de vapor en el receptor de un sistema termosolar de torre central", por lo tanto, los artículos publicados están concordancia con este objetivo. En la primera etapa de la tesis, se trabajó en la parte experimental, la idea original era implementar un prototipo de un receptor plano con aletas como receptor termosolar para la generación directa de vapor de agua. Primero se realizó un estudio calorimétrico de este receptor, con la finalidad de ver el potencial térmico del campo de pruebas de heliostatos (CPH), así como la operación del sistema experimental. En esta primera etapa se concluyó que la potencia térmica que aporta actualmente el CPH no es suficiente para la generación directa de vapor. Los resultados de esta etapa experimental se publicaron en el artículo "*Thermal analysis of a finned receiver for a central tower solar system"* en la revista Renewable Energy (indizada en el JCR), y en el artículo de ponencia internacional "*Experimental Analysis of a Flat Plate Receiver for Measurement of Low Thermal Power of a Central Tower Solar System"* publicado por AIP Conference Proceedings, en los cuales aparezco como colaborador.

Como segunda etapa se realizó el estudio teórico, donde lo primordial consistió en obtener una metodología numérica que fuese capaz de reproducir el fenómeno a estudiar (generación directa de vapor utilizando radiación solar concentrada). Se realizó una exhaustiva y especializada revisión bibliográfica, de la cual se concluyó principalmente el tipo de receptor solar que se estudiaría (receptor tubular externo), los modelos matemáticos a implementar y la obtención de datos experimentales para la validación de la simulación numérica. Una vez que se definió la metodología a seguir, esta se fue puliendo con ayuda de los resultados experimentales obtenido de la literatura. Con la finalidad de ver el alcance de esta metodología se realizó un estudio paramétrico en 2D bajo un flux solar uniforme en toda la superficie externa del tubo receptor, como una primera aproximación del problema a resolver. En este estudio se observó el efecto de la generación de vapor variando el flux másico, el flux de calor y la longitud del sistema. Los resultados de este trabajo se publicaron en la revista de la Sociedad Mexicana de Ingeniería

Mecánica: Tecnología y Desarrollo (la cual esta indizada en el catálogo de revistas científicas de Conacyt), con el título "*Computational Modeling of Direct Steam Generation in Pipes Receiving Concentrated Solar Radiation*" en el cual aparezco como primer autor.

En la tercera etapa se planteó una situación más cercana a la realidad. Se pasó a un sistema 3D, bajo las consideraciones principales de tener un flux solar uniforme aplicado en la mitad del tubo receptor, puesto que en los sistemas reales solo un área del receptor es iluminada. En esta etapa se hizo un estudio paramétrico en el cual se varió la magnitud del flux másico y del flux de calor. Los resultados de este estudio se publicaron en el artículo "*Three-dimensional numerical study of direct steam generation in vertical tubes receiving concentrated solar radiation"* en la revista International Journal of Heat and Mass Transfer (indizada en el JCR). En este artículo también aparezco como primer autor. Como continuación del estudio anterior, se hizo el estudio de un sistema variando el efecto de la uniformidad del flux solar. Se observó que la distribución del flux de calor solar afecta el proceso de generación de vapor. Los resultados de este estudio se publicaron en el artículo *"Effect of non-uniform concentrated solar flux on direct steam generation in vertical pipes of solar tower receivers"* en la revista *Solar Energy* (indizada en el JCR). En este artículo aparezco como primer autor.

De manera general se puede concluir que, con los resultados obtenidos se cumplió con los objetivos planteados en este trabajo Doctoral. Como complemento a la relatoría se anexan las publicaciones mencionadas previamente.

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Thermal analysis of a finned receiver for a central tower solar system

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ABSTRACT

In this study, a thermal analysis of a finned receiver prototype for a thermosolar tower system is presented. The experimental system consists of parallelepiped aluminum enclosure of 1.2 m high, 1.23 m wide and 0.1 m depth. At the interior, 1232 cylindrical fins with a diameter of 0.0095 m (3/8″) and 0.09 m length increases the heat transfer area up to 225%. The vertical wall receives the incoming solar concentrated radiation from a group of heliostats whilst at the interior a constant flow of water removes the absorbed energy. Experimental temperature profiles were obtained at different heights and depths and a comparison was made with numerical results obtained with the use of commercial CFD software. It was found that the maximum thermal efficiency of the receiver was 94.4%, decreasing as the radiative flux increases.

1. Introduction

Despite global efforts to reduce the emissions of CO_2, the current economic systems are still based on fossil fuels. It is noteworthy that global energy system who has been increasing life standards of the humanity it is one of the causes of a global weather destabilization that with only a 2 °C raise of global temperature could cause major changes in social and natural global systems. However, the concentrating solar thermal systems are one of the options (CST), in the renewables energies spectrum, to face this problem and consolidate the non-emissions energy system era. The central receiver system (CRS) concept has advantages like readily integration in fossil plants for hybrid operation, higher temperatures (up to 1000 °C) and thereby higher efficiency and may operate using thermal storage for more than 20 h by day [1].

To create research infrastructure for the development of solar thermal tower technology in Mexico, on October 28, 2011, the Heliostat Testing Field (CPH) was inaugurated in the University of Sonora (Fig. 1) [2]. The installation is part of the National Laboratory of Solar Concentration and Solar Chemistry (LACYQS), co-funded by CONACYT, UNAM and the University of Sonora. The CPH is the first of its kind in Mexico, which will allow the development of research and technological development to take advantage of the abundant solar radiation of Northwest Mexico (of the best in the world) as an alternative for the generation of electric energy and heat for industrial processes. As part of the development process, it is considered very relevant to analyze in detail the thermal behavior of the installed receiver, which has been used to estimate the thermal power provided by a small number of heliostats. Currently, CEToC has 40 heliostats: 5 of 1.5 m^2, 5 of 2.25 m^2, 1 of 6 m^2 and 29 of 36 m^2 for a total reflective area of 1100 m^2 (70% of this area is operational and the rest is in rehabilitation).

In specialized literature, there are reported several studies related to thermal analysis in CRS receivers. Up next, some of these studies are categorized and presented briefly.

1.1. Analysis of thermal losses in cavity receivers

Hess and Henze [3] realized a natural convection investigation in open cavities. Obtaining detailed velocity profiles using laser Doppler for Rayleigh numbers between 3×10^{10} and 2×10^{11}, corresponding to a high-temperature boundary condition. Flux patterns exhibit two and three-dimensional behaviors; reported patterns of transitional to turbulence boundary layer and flux patterns in and out of the cavity. Chan et al. [4] experimentally investigated the natural convection in a 2D open cavity using laser

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Nomenclature

A: Receiver width, (m)
Ar: Inner hot surface area, (m2)
Cp: Specific heat at constant pressure, (J/kg K)
D: Inlet pipe diameter, (m)
g: Gravitational acceleration, (m/s2)
Gk: Generation of turbulent kinetic energy due to the buoyant force, (J/kg)
Gr: Grashof number, nondimensional
H: Receiver height, (m)
h: Average convective heat transfer coefficient, (W/m2 K)
k: Turbulent kinetic energy, (m2/s2)
L: Receiver length, (m)
$\dot{m}$: Mass flow, (kg/s)
Nu: Average Nusselt number of the heated wall, nondimensional
qcal: Calorimetric heat flux, (W/m2)
qHFS: Radiative heat flux, (W/m2)
Pk: Generation of turbulent kinetic energy, (J/kg)
Ra: Modified Rayleigh number at the heated wall, nondimensional
Re: Reynolds number at the inlets, nondimensional
T_{amb}: Ambient temperature, (K)
$\overline{T_h}$: Average temperature of the hot wall, (K)
$\overline{T_i}$: Average temperature of the inlets, (K)
T_∞: Temperature of the bulk fluid, (K)
U: Inlet velocity, (m/s)
x, y, z: Coordinate system, (m)
i, j, k: Unity vector components

Greek symbols

α: Thermal diffusivity, (m2/s)
β: Thermal expansion coefficient, (1/K)
ε: Turbulent kinetic energy dissipation, (J/kg)
ε_r: Emissivity, nondimensional
η: Efficiency, nondimensional
λ: Thermal conductivity, (W/m K)
μt: Turbulent viscosity, (kg/m s)
ν: Kinematic viscosity, (m2/s)
ρ: Density, (kg/m3)
σ_t: Turbulent Prandtl number, nondimensional
ω: Turbulent specific dissipation rate, nondimensional

Experimental analysis of a flat plate receiver for measurement of low thermal power of a central tower solar system

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NOMENCLATURE

A_R	Receiving area, m^2.
E1, E2, E3	Refers to the results of Experiment 1, 2 and 3
Cp	Specific heat, J / kg K.
g	Gravity, m/s^2.
D	Diameter, m
X	Horizontal distance (Receiver width), cm.
Y	Vertical distance (Receiver Height), cm.
Z	Depth Distance, cm, mm.
$\dot{Q}_{cal}$	Heat removed by the thermal fluid, kW.
$\overline{Re}$	Average Reynolds number, nondimensional.
T_{in}	Mean temperature inlet, K.
T_{out}	Mean temperature outlet, K.
T_∞	Temperature of bulk fluid, K.
∇T_z	Temperature gradient in the z-direction, K/cm.
U	Inlet average flow velocity, m/s.
ΔT_w	Difference in average water inlet and outlet temperatures, K.
ΔT_f	Difference in temperature in the fin, K.
ΔZ	Difference in depth of fin, cm.
$\dot{V}$	Volumetric flow, m^3/s
η	Minimum thermal efficiency, %.
$\bar{q}_{sensor}$	Radiative Flux average, W/m^2
DNI	Direct normal solar radiation, W/m^2.

Greek symbols

ε	Emissivity, nondimensional.
λ	Thermal conductivity, W/m K.
μ	Viscosity, kg /m s.
ρ	Density, kg/m^3.
σ	Standard deviation.

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Computational Modeling of Direct Steam Generation in Pipes Receiving Concentrated Solar Radiation

Modelación Computacional de la Generación Directa de Vapor en Tuberías que reciben Radiación Solar Concentrada

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Abstract

The purpose of this work was to simulate the conditions of direct steam generation in a vertical tube receiving concentrated solar radiation. The modified RPI model was used for the conditions of critical heat flux coupled to a Eulerian two fluid model. The mathematical model was solved with CFD software ANSYS FLUENT v15. The results were validated with experimental data reported in the literature and a parametric study was carried out to determinate the effect of the mass flux, the heat flux incident on the wall and the heat transfer area on: the steam quality, the volumetric fraction and the temperatures of liquid and steam. From the results obtained, it was determined the required conditions to obtain a steam quality of 100%.

Resumen

El propósito de este trabajo fue validar una estrategia numérica capaz de simular condiciones de generación directa de vapor en un tubo vertical. Se utilizó el modelo RPI modificado para condiciones de flujo de calor crítico acoplado a un modelo Euleriano de dos fases, según la bibliografía especializada consultada se seleccionaron los modelos que predijeron los mejores resultados como: lo sitios de nucleación activa, frecuencia y diámetros de desprendimiento de salidas de las burbujas además de los coeficientes de transferencia de calor entre las fases. El modelo matemático se resolvió con el software de CFD ANSYS FLUENT v15. Se validaron los resultados con datos experimentales reportados en la literatura. Se analizó el efecto del flux másico, el flujo de calor incidente en la pared del tubo y el área de transferencia de calor sobre: la fracción volumétrica, la calidad del vapor y las temperaturas del líquido y el vapor. A partir de los resultados obtenidos, se determinaron las condiciones que permiten obtener una calidad del vapor de 100 %.

Keywords:
Direct steam generation, Concentrated solar energy, Computational modelling

Palabras clave:
Generación directa de vapor, energía solar concentrada, modelación computacional

Introduction

The current global energy system that supports the living standard of humanity is one of the most important causes of global climate change. It is estimated that greenhouse gas emissions from burning fossil fuels have caused an increase in the global temperature of the earth, causing significant changes in different natural events such as intensity of hurricanes, droughts, floods, etc. On the other hand, concentrating solar thermal systems (CST) are one of the options inside renewable energies to face this problem and consolidate the era of the emission-free energy system. There are several CST technologies (parabolic trough, central tower, linear Fresnel, Dish-Stirling, etc), however, the solar central tower system (SCT) concept has advantages like readily integration in fossil plants for hybrid operation, higher temperatures (up to 1000 °C) and thereby higher efficiency and may operate using thermal storage for more than 20 hours by day [1]. Some SCT power plants directly use high-pressure water with direct steam generation technology (DSG). The thermal receiver of SCT plants with DSG operates with a bank of vertical tubes which receive concentrated solar energy from the heliostats field.

Hirsch et al. [2] realized a study focused on plants with DSG and found that by eliminating heat exchangers and conventional working fluids (synthetic oils or molten salts), the operating costs can be reduced significantly. In addition, the investment costs are also reduced to the elimination of the intermediate equipment that occupies the conventional CST [3]. C. Prieto et al. [4], reported that there are four solar plants in the world that operate with DSG technology in central tower systems, two with saturated steam (PS10 and PS20), installed in Seville Spain and operating commercially since 2007 and 2009, respectively, and two with superheated steam: Ivanpah Solar Project (located in California, United States and in operation since 2013) and Khi Solar One (located in South Africa and in operation since 2016). In the specialized literature, several numerical studies focused on the direct steam generation (DSG) have been found from concentrated solar energy [5-8], but none of these gives information on the phenomenon of phase change that occurs in SCT systems. The studies of DSG based on Computational Fluid Dynamics (CFD) are briefly described next.

Greek letters

α	Volume fraction, -
ρ	Density, kg m^{-3}
μ	Viscosity, kg s^{-1} m^{-1}
ΔT_{sub}	Subcooled temperatura (T_w-T_{sat}), K
λ	Thermal diffusivity, m^2 s^{-1}
φ	Contact angle, deg. / °
σ	Surface tension, N m^{-1}
μ^{bt}	Viscosity due to bubble induced turbulence, kg s^{-1} m^{-1}
k	Turbulent kinetic energy,
ε	Rate of dissipation,

Abbreviations

CST	Concentrating Solar Thermal Systems
CST	Central Solar Tower
DSG	Direct Steam Generation
CFD	Computational Fluid Dynamics
VOF	Volume of Fluid
RPI	Rensselaer Polytechnic Institute
ONV	Onset of Nucleate Boiling
NVG	Net Vapor Generation

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Three-dimensional numerical study of direct steam generation in vertical tubes receiving concentrated solar radiation

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ABSTRACT

Concentrated solar thermal energy is a good alternative to mitigate the environmental impacts generated by the growing use of energy. There are several commercial solar power tower plants in the world operating with direct steam generation. These plants operate with cavity-type and external tubular receivers. The conventional tubular receivers consist of a set of vertical circular tubes through which the working fluid circulates. This study is focused to analyze in detail the direct steam generation in a vertical tube receiving concentrated solar radiation. The mathematical model is based on the equations of continuity, momentum and energy for each phase. The modified model of Rensselaer Polytechnic Institute was used for the conditions of critical heat flux coupled to a Eulerian two fluid model. In the modified model of Rensselaer Polytechnic Institute, the total heat flux is divided into four components from the wall to the liquid: (a) liquid-phase convective heat flux, (b) heat transfer due to quenching, (c) heat flux due to evaporation and (d) convective heat flux of the vapor phase. The mathematical model was solved with a computational fluid dynamics software. The results were validated with experimental data reported in the literature and a parametric study was carried out to determinate the effect of the mass flux and heat flux incident on the wall, on: the steam quality, the volumetric fraction, the enthalpies and temperatures of liquid and steam. The reduction of mass flux by 44% increased the output mass flow of steam 4.28 times, whereas the increase of concentrated solar flux by 40% increased the output mass flow of steam 4 times.

1. Introduction

In order to mitigate the environmental impacts generated by the use of current fossil energy sources, is necessary to develop new technologies that generate clean energy (free of CO_2 emissions). In this sense, concentrated solar thermal energy (CSP) is a good alternative to help meet this goal [1]. The CSP technologies are: (a) central tower system, (b) parabolic dish, (c) parabolic channel and (d) linear Fresnel. The central tower system is considered one of the future trends of CSP technologies, due to its potential to reach high temperatures (greater than 800 K) [2].

In central tower systems, reflecting mirrors (heliostats) are used, which concentrate the solar radiation in a receiver located at the top of a tower. The role of the receiver is to transfer concentrated solar energy to a thermal fluid. In the classical process, the thermal fluid enters a heat exchanger, where it transfers its energy to produce water vapor at high temperature and pressure, which is directed to a turbine coupled to an electric generator.

Direct steam generation (DSG) is an alternative process to produce electrical energy in systems with CSP. The process is like the classic one, but in this case, the steam is generated directly in the receiver, being able to leave saturated or overheated. Among its advantages are the reduction of operation and maintenance costs and the increase of the overall efficiency of the plant [3–5]. On the other hand, another application of the DSG is the production of steam for industrial processes [6].

Currently there are four commercial plants in the world of central tower with DSG, two operates with saturated steam: PS10 and PS20, and two with superheated steam: Ivanpah Solar Project, and Khi Solar One [5]. These plants operate with cavity-type and external tubular receivers. The conventional tubular receivers consist of a set of vertical circular tubes through which the working fluid circulates (Fig. 1).

The CSP technology with DSG, requires detailed studies to understand the phenomenon of steam production that occurs in a tube that receives a very high heat flux on its surface. The most recent works focused on theoretical analysis of the DSG classified by the type of CSP technology are briefly described below.

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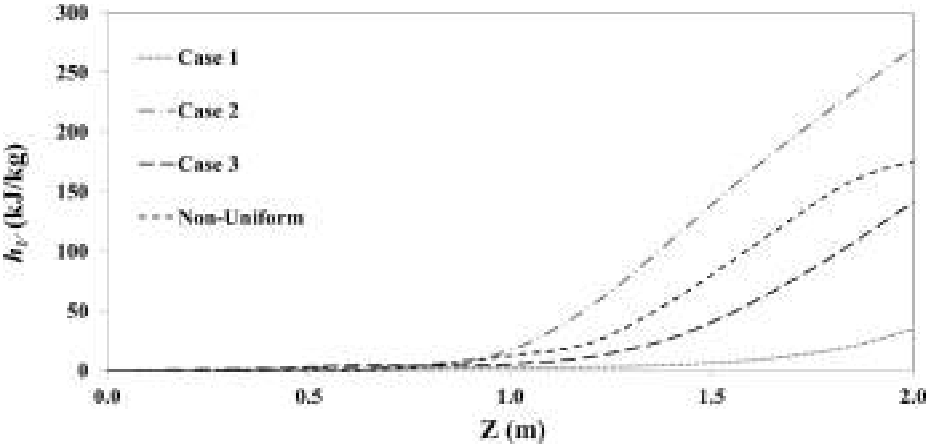

Fig. 33. Variation of average vapor enthalpy with tube height.

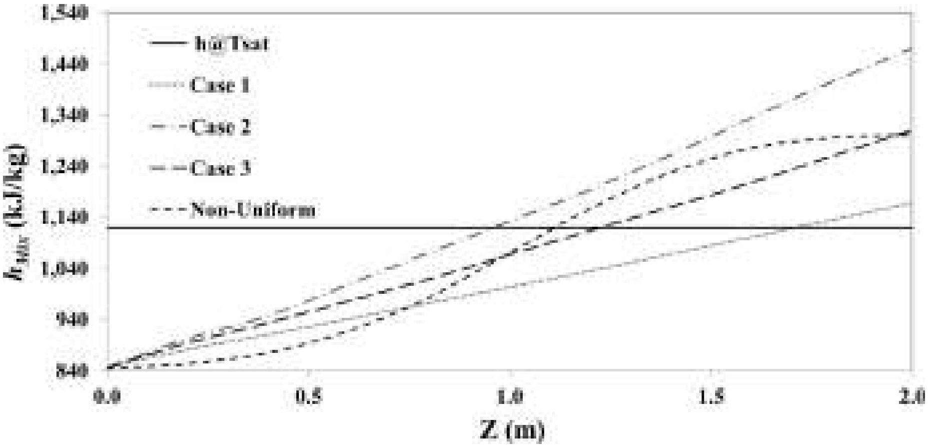

Fig. 34. Variation of average mixture enthalpy with tube height.

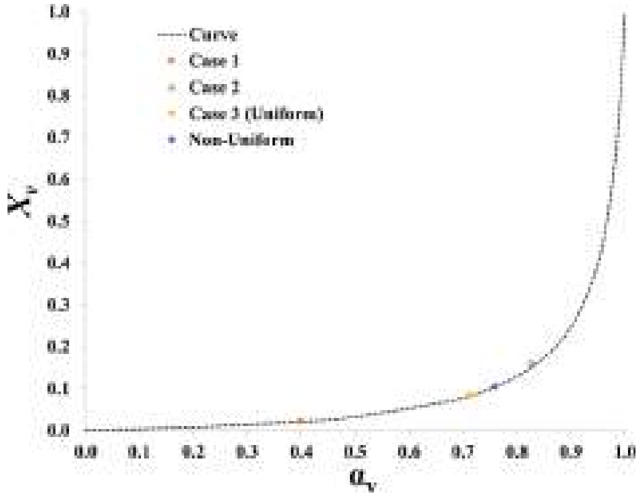

Fig. 35. Relationship between average $\overline{\alpha}_v$ and X_v for each case.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheatmasstransfer.2019.03.101.

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liquid develop the same behavior. A maximum value is reached which is above the T_{sat} and then descend to the output of the system.

5. Once the saturation of the system is reached, the profiles of the volume fraction and the vapor quality maintain a behavior defined by the non-uniformity of the applied solar flux.
6. The NVG point is achieved around the point where the system reaches saturation.

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