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MODELING A BOILING PROCESS UNDER UNCERTAINTIES

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Теплообмін у процесі кипінні залежить від цілої низки чинників (стадії кипіння, фізичних та геометричних параметрів, змінних стану і умови обтікання). Всі варіанти засновані на емпіричних співвідношеннях, отриманих на базі експериментальних даних, оскільки досі відсутня узагальнена теорія темплообміну. Із збільшенням перегріву стіни (Tw-Ts) випаровування змінюється від конвективного кипіння до ядерного, а відтак – до film-кипіння. Для розрахунку коефіцієнта тепловіддачі кожного типу кипіння існують окремі рівняння. Існує можливості враховувати невизначеність в динамічному моделюванні кипіння. Для цього була розроблена нечітка модель типу Такагі-Сугено, яка містить нечіткі переходи між стадіями кипіння.

Ключові слова: процес кипіння, теплообмін, динамічне моделювання кипіння, нечітка модель Такагі-Сугено.

Теплообмен при кипении зависит от целого ряда факторов (стадии кипения, физических и геометрических параметров, переменных состояния и условия обтекания). Все варианты основаны на эмперических экспериментальных данных, так как до сих пор отсутствует общая теория теплообмена. С увеличением перегрева стены (Tw-Ts) испарение изменяется от конвективного кипения до ядерного, а затем до film-кипения. Для расчета коэффициента теплоотдачи каждого типа кипения существуют отдельные уравнения. Существует возможность учитывать существующую неопределенность в динамическом моделировании кипения. В связи с этим была разработана нечеткая модель типа Такаги-Сугено, включающая в себя нечеткие переходы между стадиями кипения.

Ключевые слова: процесс кипения, теплообмен, динамическое моделирования кипения, нечеткая модель Такаги-Сугено.

The heat transfer during boiling depends on a variety of factors (boiling stage, material parameters, geometrical parameters, state variables and flow conditions). All variations are based on empirical relationships gained from experimental data because there is still no comprehensive theory. With increasing wall superheat (Tw-Ts), the evaporation changes from convective boiling to nucleate boiling and then to film boiling. For each type of boiling, separate equations for the calculation of the heat transfer coefficient do exist. This paper presents possibilities to take account of the existing uncertainties in the dynamic simulation of boiling. For this reason a Takagi-Sugeno-fuzzy-model was developed which includes the fuzzy transitions between the boiling stages.

Key words: the process of boiling, heat transfer, dynamic simulation of boiling, fuzzy model of Takagi Sugeno.

Introduction. Steam production is the basic process for the generation of electrical energy in nuclear or coal power plants. By means of the flow type, the boiling process can be distinguished between pool boiling and flow boiling. Pool boiling occurs in free flow. In a forced flow the evaporation process is called flow boiling. Undercooled boiling is not investigated. The medium has reached its saturation temperature.

The boiling process can be subdivided in three stable stages:

– convective boiling,

– nucleate boiling

– and critical boiling states (film boiling or dryout of the heated surfaces).

The transitions between the boiling stages are not sharp and they are determined by the wall superheat ΔT. The wall superheat is the difference between the wall temperature T_W and the saturation temperature of the fluid T_S. The saturation temperature remains constant in the boiling process. The heat transfer is determined by the heat transfer coefficient α. The correlations are shown in the following figure. The abscissa is the logarithmic temperature difference (T_W-T_S) and the ordinate shows the heat flux density.

The boiling process begins with convective boiling. The wall temperature is only a few Kelvin above the saturation temperature. No or only very few bubbles are formed. The increase of the wall temperature increases the bubble formation and the convective boiling changes over to nucleate boiling. Point A marks the onset of nucleate boiling, ONB [1].

The bubbles form on cavities or scratches on the surface containing pre-existing gas/vapor nuclei. The rising bubbles mix the fluid and thus improve the heat transfer. This is demonstrated by the growing increase of the heat transfer coefficient. Further increase of the heat supply causes also an increase in bubble formation and the flow of fluid to the wall is lower. At a maximum heat flux density (point C, called the critical heat flux CHF) forms a closed vapor film restraining the heat transfer. This means that the transferred heat flow decreases, then reaches a minimum (Leidenfrost point) and increases. This behavior is achieved by setting the wall temperature. The evaporation process in nuclear or coal power plants is setting the heat flow. This means that due to the suddenly worsened heat transfer, the wall

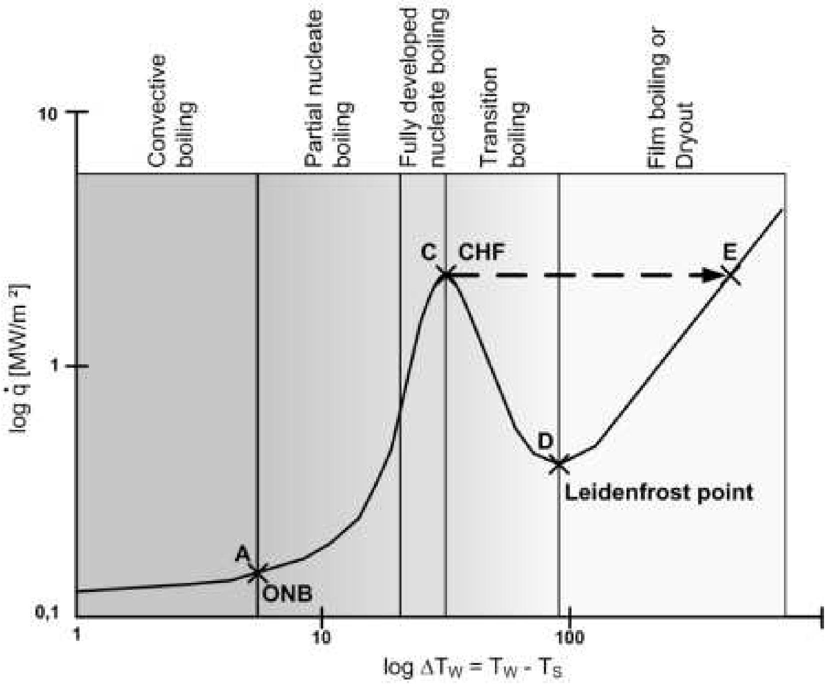


Figure 1 – Explanation of the boiling stages based on the boiling curve of Nukiyama

temperature increases drastically (dashed line from C to E) [2].

Mathematical description of the boiling process. The describing variable for the modeling of the heat transfer is the heat transfer coefficient α. For each boiling stage many formulas do exist which mostly are based on experimental data. Besides viscosity, thermal conductivity, density, thermal expansion coefficient and geometrical parameters the heat transfer depends on many influencing factors. During heat transfer with phase change, the number of variables is extended by enthalpy of vaporization, saturation temperature, vapor density and surface tension. Microstructure and material of the heating surface are relevant as well. The multitude of influencing factors and their complex interaction are the cause that no comprehensive theory could be developed yet. Thus, all mathematical calculations are based on empirical or semi-empirical relations [2].

Convective boiling

The calculation of the heat transfer coefficient α is based on the equations for forced convective heat transfer [2].

Nucleate boiling

The heat transfer coefficient for nucleate boiling is described by empirical models. The equation refers to a standard state with α_0 and $\dot{q}_0$ and considers the relative effects of wall roughness C_W, the boiling pressure by F(p*) and n and the pipe diameter [2].

Critical boiling states

Film boiling

The heat transfer coefficient for film boiling is composed of the heat transfer coefficient α_L and α_S. The heat transfer coefficient α_L is determined by the heat conduction process through the vapor layer and α_S through the heat radiation process [2]. The explicit equation of Bromley's proximity for the technical area of interest is defined in [4].

Dryout

The calculation of the heat transfer coefficient α is based on the equations for forced convective heat transfer [2].

Takagi-Sugeno-Fuzzy-Model. To model the fuzzy transition between the boiling stages, a Takagi-Sugeno fuzzy model is suitable. The height of the wall superheat is the decision criterion, which boiling stage is present. For this reason it is fuzzified and ΔT is defined as a linguistic variable (Figure 2), which consists of three membership functions "small", "medium" and "large". Convective boiling is definitely given if the wall superheat is located between 0 K and 7 K ("small"), we speak of nucleate boiling , when ΔT is between 20 K and 35 K ("medium") and critical boiling states starts at a high temperature of 100K ("large"). The transition regions are modelled linearly. The data were taken from Figure 1. The decision which mechanism works of the critical boiling states is based on the critical vapor content. If the vapor content x is low, then it is film boiling, is it “high” then works the heat transfer mechanism dryout of the heating surface.

The following rule base is derived:

If ΔT = "small" then α = convective boiling
If ΔT= “medium" then α = nucleate boiling
If ΔT = "large" and x = “low”
then α = film boiling
If ΔT = "large" and x = “high”
then α = film boiling (1)

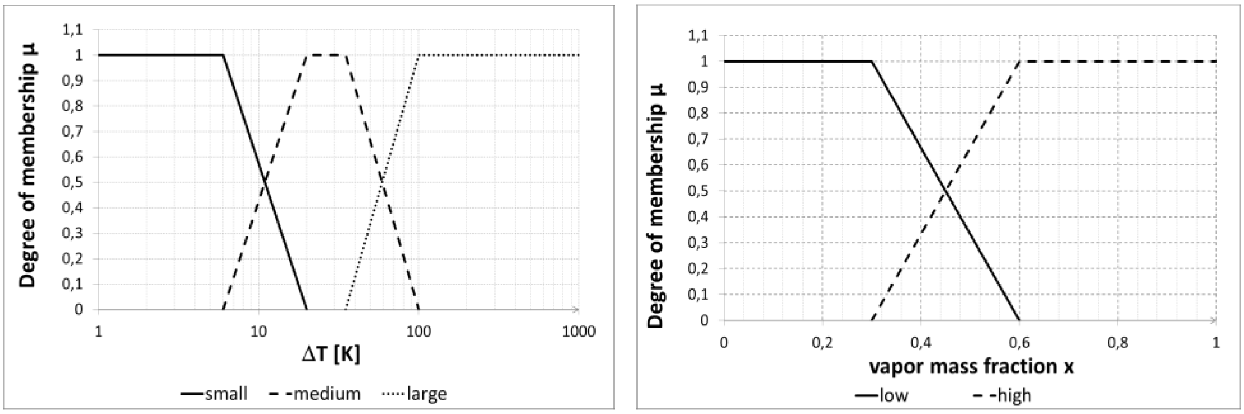
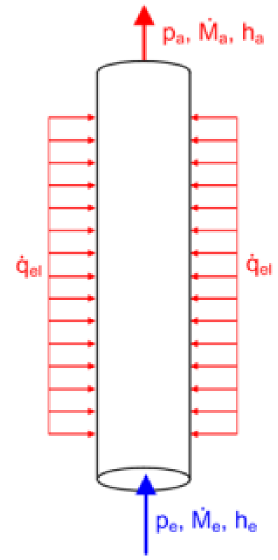


Figure 2 – Linguistic variable "wall superheat ΔT" and "vapor mass fraction x"

Subsequently, the accumulation is performed to determine the resulting heat-transfer coefficient.

Modeling a boiling process. To illustrate the methods / procedures developed, the following boiling process is applied (Figure 3). In an electrically heated thin-walled pipe is saturated water supplied and vaporized over the pipe length. The dynamic behavior is described by following simplified non-linear differential equation system (Assumption: the pressure is constant).



p_e, p_a – Inlet- outlet pressure;
$\dot{M}_e$, $\dot{M}_a$ – Inlet- outlet mass flow;
h_e, h_a – Inlet- outlet enthalpy;
m_W – Pipe mass;
c_W – Heat capacity of pipe wall;
m – Mass of the medium;
T_W – Wall temperature;
$\dot{q}_{el}$ – Electrical heat flux

Figure 3 – Model for describing a boiling process

Heat balance medium:

$$\left(q_m \cdot V + V \cdot h_e \cdot \frac{\partial q}{\partial h} - V \cdot h_m \cdot \frac{\partial q}{\partial h}\right)\frac{dh_m}{dt} + 2\dot{M}_e \cdot h_m = \\ = 2\dot{M}_e \cdot h_m + \alpha \cdot A \cdot \left(T_W - T_{M_m}\right). \qquad (2)$$

Heat balance pipe:

$$m_W \cdot c_W \cdot \frac{dT_W}{dt} = Q_{ei} - \alpha \cdot A \cdot \left(T_W - T_{M_m}\right). \qquad (3)$$

The realization of the model equations is carried out with a computer algebra system. The heat flux density is given. After 10 seconds the heat flux density increases (Figure 4, left). At the beginning of the simulation, the fluid temperature is already at saturation temperature. This value remains constant throughout the boiling process. The simulation starts with the state of convective boiling. The heat transfer coefficient is low. For the first 10 seconds a steady state appears. The wall temperature is a few Kelvin above the saturation temperature.

With increasing heat flux density the wall temperature rises. Due to the low heat transfer coefficient, the wall temperature initially rises steeply. With the onset of bubble production the water is getting mixed and the heat transfer improves. This means that the heat transfer coefficient increases and the wall temperature rises slower despite constantly increasing heat supply. The heat transfer to the water improves until the critical point is reached, so that the bubbles form a closed vapor film. The steam has considerably poorer heat transfer properties. That means for a given heat flux density, that the wall temperature (Figure 5) changes almost in a jump-like way and the process switches to stable film boiling. In right Figure 4 shows the heat flux over the wall superheat. When the critical heat flux is reached, then the wall superheat rises steeply.

Summary and Outlook

The article presents a possibility to take account of an aspect of model uncertainty. In a first step, the heat transfer coefficient for the dynamic simulation of boiling process is realized with a Takagi-Sugeno-fuzzy-model and integrated into the differential equation system. The dynamic simulation of the process example represents the process behavior realistically.

To extend the model, the parameter uncertainties for the major variables (e.g. pressure, temperature) are considered as fuzzy and in the simulation.

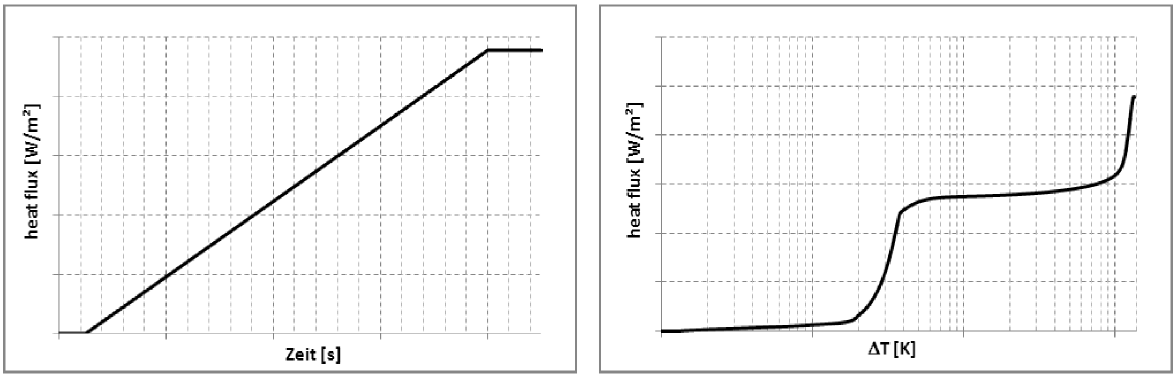


Figure 5 – Temporal course of the prescribed heat flux (left) and qualitative trend of the heat flux over the wall superheat T (right)

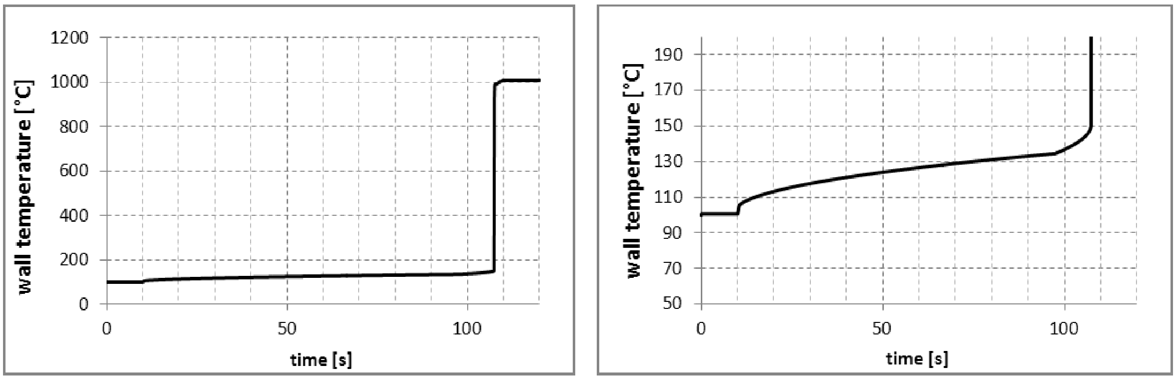


Figure 5 – Qualitative temporal course of the wall temperature, left) overview right) zoomed

Acknowledgments

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References

1 Kandlikar S.G. Handbook of phase change: boiling and condensation / S.G.Kandlikar // Taylor & Francis. – 1999.

2 Stephan K. Wärmeübergang beim Kondensieren und beim Sieden / K.Stephan // Springer-Verlag, Berlin Heidelberg. – 1988

3 Gorenflo D. VDI Heat Atlas, chapter Hab / D.Gorenflo // Springer-Verlag, Berlin Heidelberg. – 2006.

4 Bromley L.A. Heat Transfer in Stable Film Boiling / L.A.Bromley // Chem. Eng. Progress, v.46, №5. –1950.

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