FACULTY OF MECHANICAL ENGINEERING CTU IN PRAGUE

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Doctoral study programme / Field of Study: Mechanical Engineering / Power Engineering

Dynamics of Heat Transfer During Cooling of Overheated Surfaces

Introduction

Cooling of overheated surfaces also known as quenching is still not well-known. Quenching is defined as an onset of rapid temperature decrease within cooled geometry by relatively cold liquid. The contact between cooled surface and coolant is not a straightforward process. If the surface temperature is high enough, liquid can't touch the surface directly, but it is separated by stable vapor layer. The layer acts as a thermal insulation barrier and the resulting heat transfer is very limited until surface temperature fails bellow so-called Leidenfrost temperature. It is a very chaotic transition process where every new experimental study is an important piece of the puzzle on the way to fully understand the phenomenon. The motivation for this study is to propose a detailed view on the quenching phenomenon, specifically bottom reflooding of an annular channel with a heated model of nuclear fuel pin. The result can serve as an input for other analytical studies in the field and it can point out several side effects accompanying the process of reflooding. These outputs can improve predictions of processes where quenching takes place, especially processes related to LOCA accident in nuclear reactor safety analyses.

Goals

- Build an experimental loop for investigation of quenching phenomenon in a flooded annular channel with three changeable tubes for consideration of accumulated heat and more real uneven heat generation
- Collect a large number of new experimental data with all relevant variables influencing the process
- Development of new approaches for experimental data evaluation and self-operational code for batch processing of individual quenching data with a built-in algorithm for correlation development
- Propose correlations for quenching and nucleate boiling temperatures, which are the main breakpoints in the process
- Propose formulas for calculations of heat transfer coefficients during the process
- Development of three-regional quenching model for further analytical studies
- Development of a correlation (or full set of correlations) for prediction of quenchfront velocity
- To point out the accompanying phenomena such as the influence of spacers and pressure peaks on the bottom flooding process

Experimental Loop and Setup

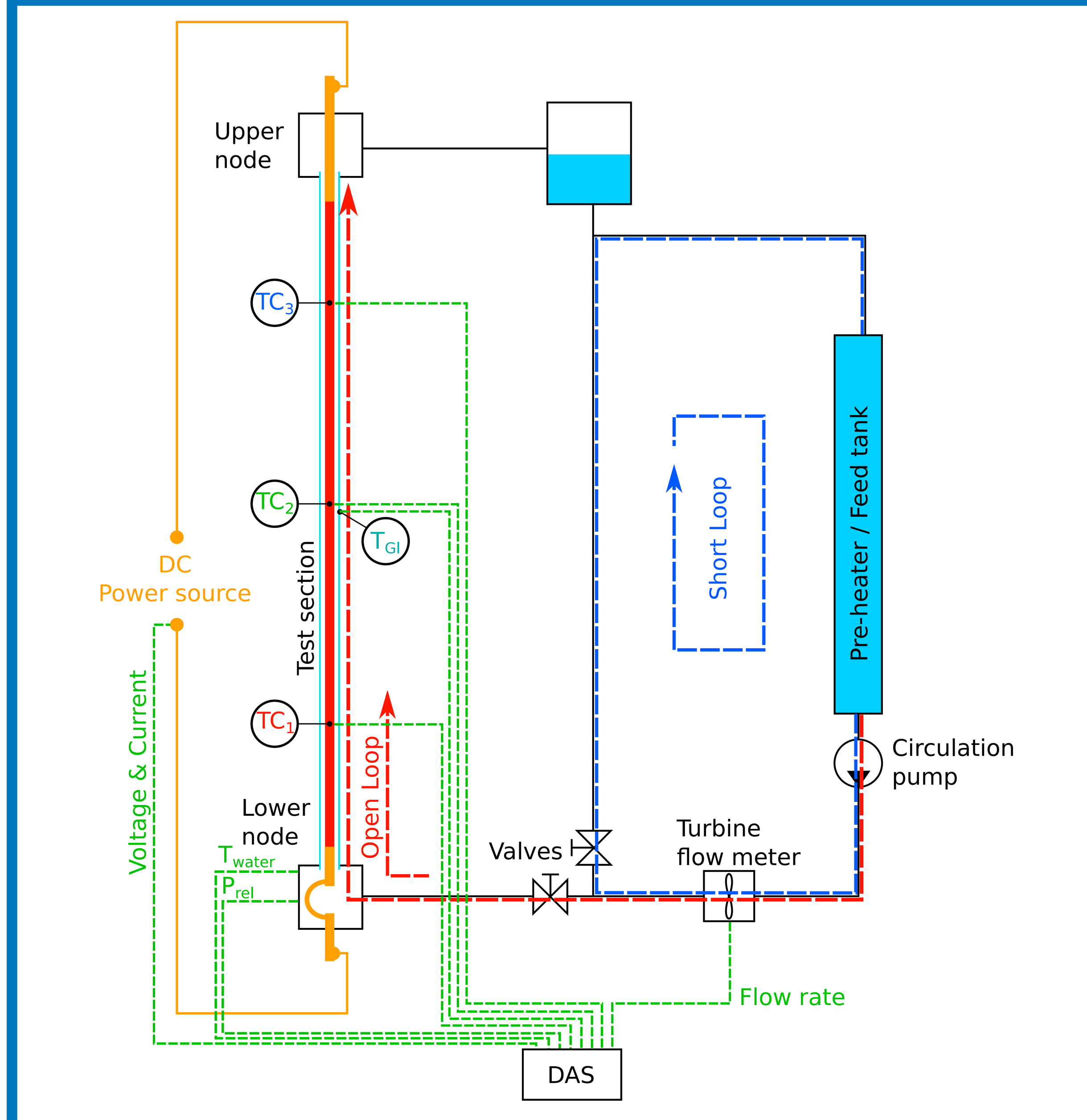


Fig.1: Experimental loop scheme

Methodology → 1 Flow rate setup → 2 Dry test section heating → 3 Flooding

Parameters of the test section	
Length	1.7 m
Coolant flow rate	80 / 110 / 190 / 270 kg/m^{2}s
Annular channel dimensions	9/14.5 mm
Initial wall temperature	250 - 700 °C (step 50°C)
Spacing of K-thermocouples	500 mm
Coolant	Water (~20°C) - atmospheric pressure

Parameters of the test section

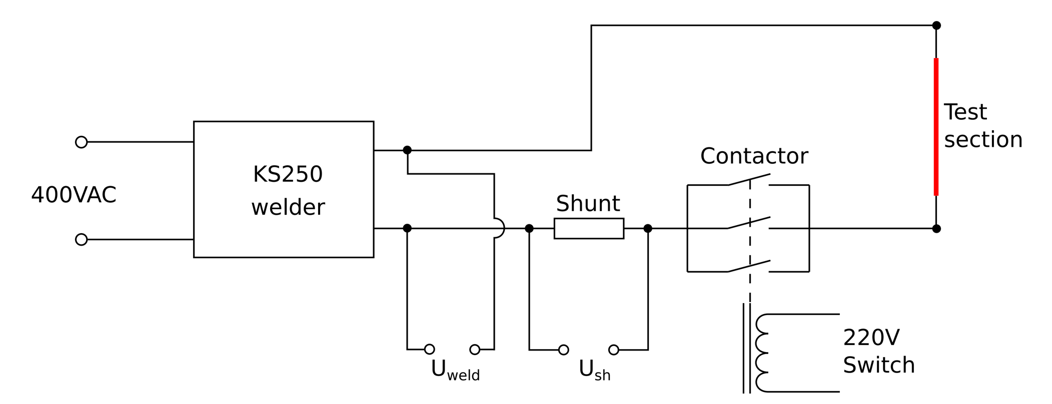


Fig.2: Power source - scheme

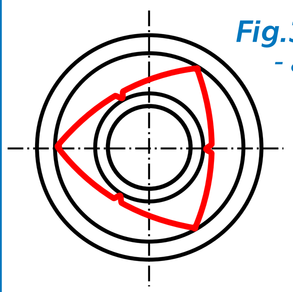


Fig.3: Design of the spacer - annular channel cross-section

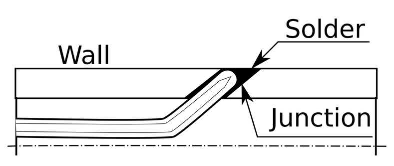


Fig.4: Installation of thermocouples

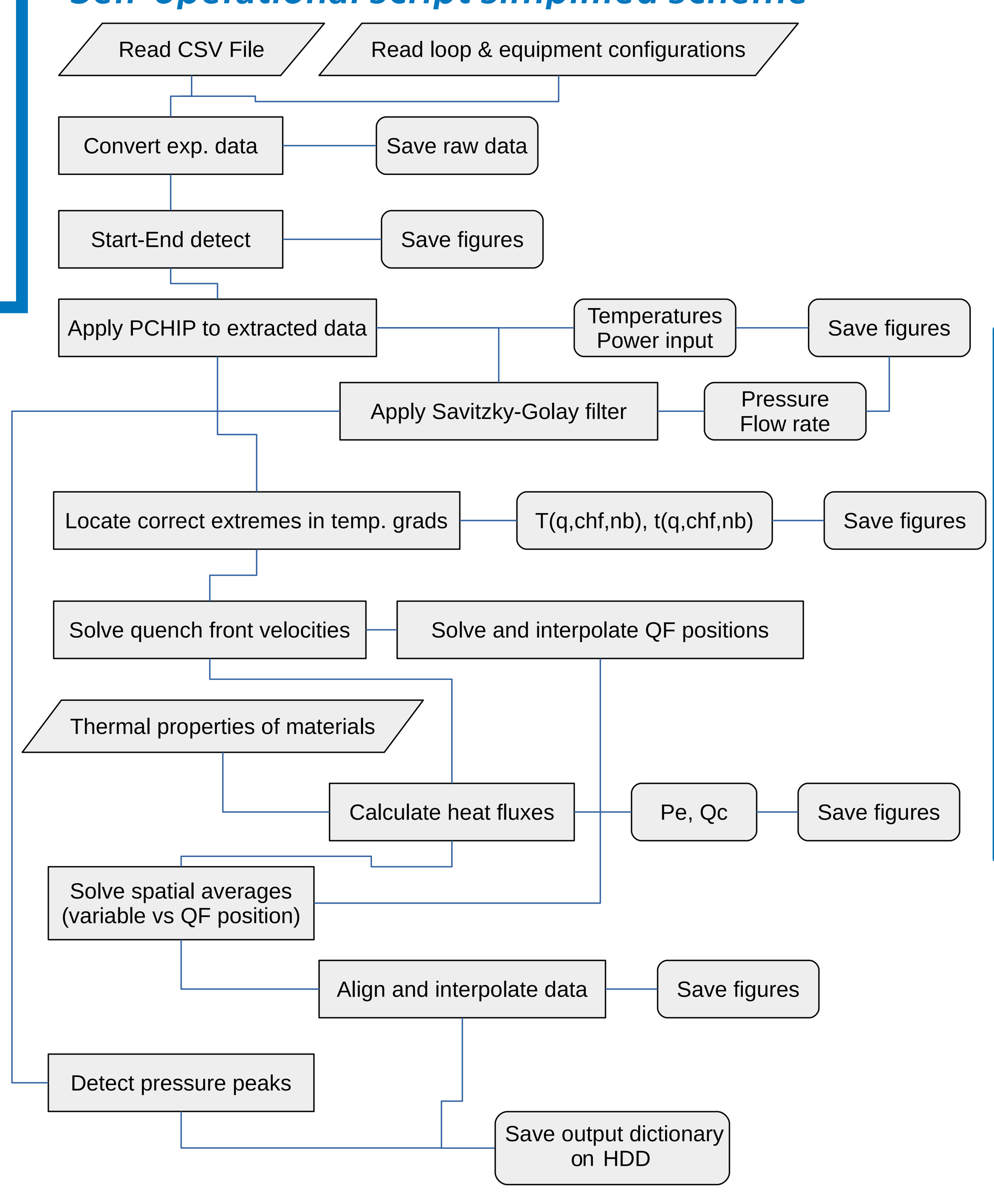
	Material	Wall thickness
Model A	Monel K-500	0.5mm
Model B	AISI 321	1.0mm
Model C	Monel K-500	f(z) - variable

Changeable fuel rod models

Individual Data Processing

Before the full-scale data evaluation, each data set passed through individual evaluation. This step contains a calculation of average quench front velocities, surface heat fluxes, evaluation of temperature profiles and its derivatives, identification of quenching and rewetting temperatures, calculation of heat transfer coefficients, pressure drops and etc. The data processing scripts are written in the Python v.3.6 programming language supplemented by numerical python libraries (NumPy v.1.14) and scientific python (SciPy v.1.0).

Self-operational script simplified scheme



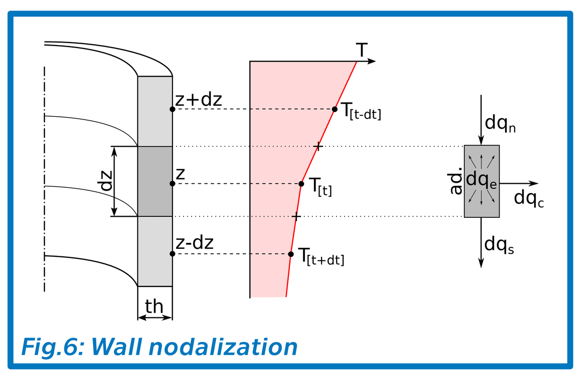


Fig.6: Wall nodalization

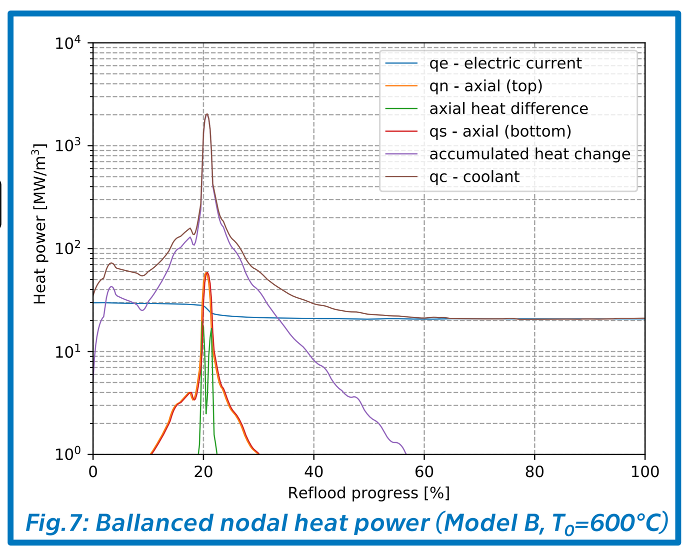


Fig.7: Ballanced nodal heat power (Model B, T_0=600°C)

1) Quenching temperature correlation

$$\overline{T_q} = \frac{1}{n} \cdot \sum_{i=1}^{n} (T_0^{2.01} \cdot \frac{[(5426e-7)\rho_{q66}]^{7.44}}{C_{q66}^{1.73} k_{q66}^{2.48}} \cdot \frac{c_{in0}^{0.15}}{\delta_i^{0.15} z_i^{0.19} P_{e0i}^{0.024}} + 84)$$

2) Relative velocity correlation

$$U_{ab} = -0.2363A^3 + 1.587A^2 - 3.701A + 3.327$$

$$A = \overline{T_0}^{-0.83} (\frac{\overline{\delta}}{\overline{T_q}})^{1/3}$$

3) Absolute quench front velocity

$$u_{ab} = U_{ab} \cdot c_{inab}$$

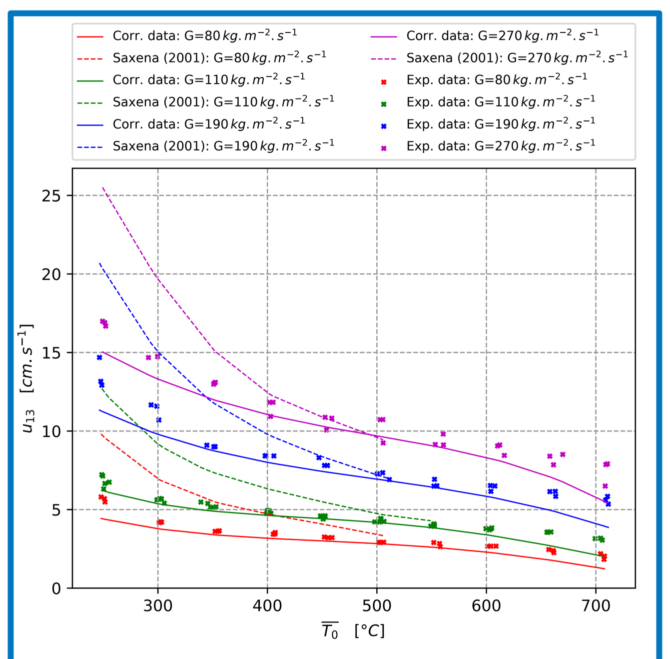


Fig.14: Validation of the correlation against experimental data and correlation by Saxena [1]

Results

Pressures

The reflood process goes with significant pressure peaks while the coolant meets the hot surface. This sudden contact generates an enormous amount of vapor due to the momentum of the coolant. The effect is clearly detectable at initial wall temperature levels above 400°C. The pressure peaks significantly influence pressure drop at the beginning of the reflood process and its value can easily exceed total pressure drop of fully reflooded test section as shows figure bellow. This can be a challenge for parallel channels, e.g. nuclear reactor core. The unevenness can lead to cooling water flowing around the central area of the core, where the surface temperature is lower, and the central area of the core can be cooled down distinctly later. Fig. 8 shows measured pressures for model B and for all four flow rate levels.

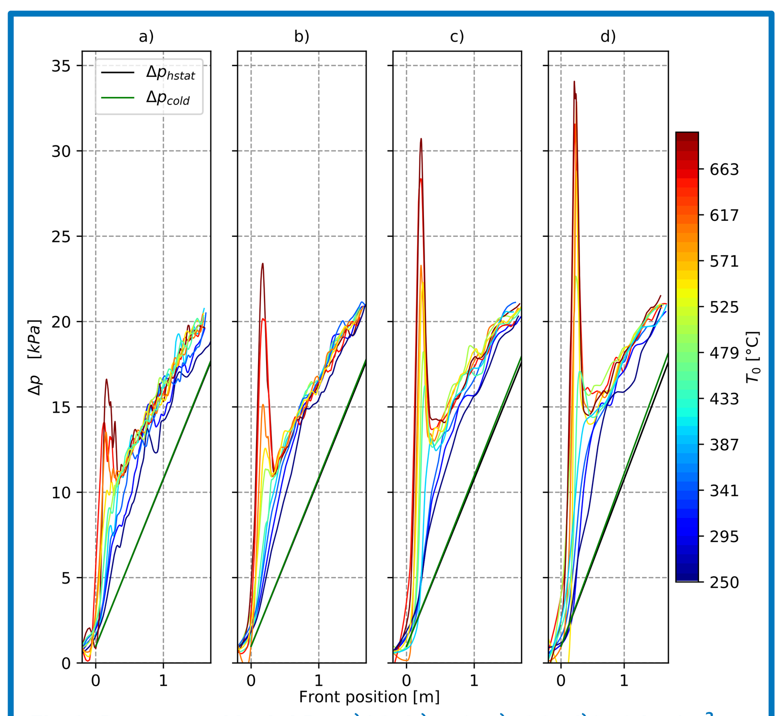


Fig.8: Pressures Model B - a)80; b)110; c)190; d)270 kg/m^{2}s

Temperatures

Surface temperatures are the most important measured parameters. For the investigated study the quenching temperature (temperature of vapor layer collapse) (Fig.10) showed to be sufficient for description of the investigated process. It strongly depends on (Fig.11):
- material properties
- initial wall temperature
- flow rate
- wall thickness
- position on the geometry.

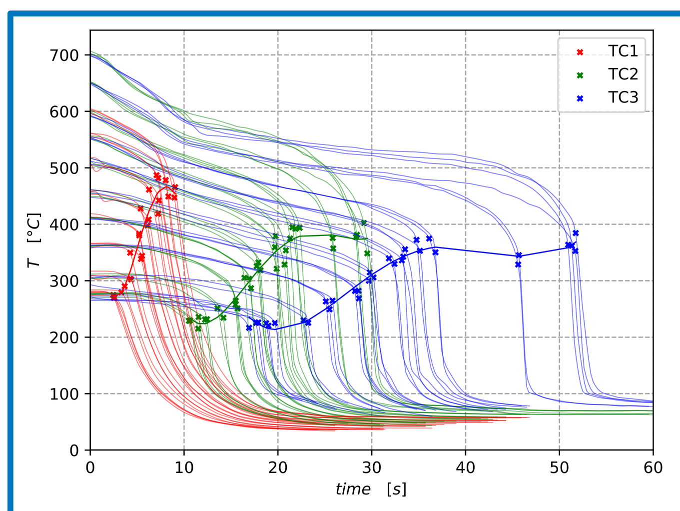


Fig.10: Temperature profiles with marked quenching temperatures

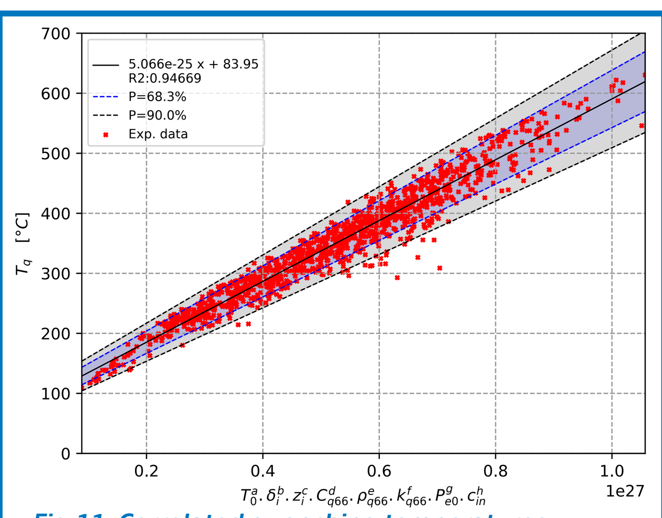


Fig.11: Correlated quenching temperatures

Heat transfer coefficients

Calculation of the heat transfer coefficient is the most tricky part of the process. The dry and two-phase region are assumed as regions cooled by steam or water-steam mixture at saturation temperature, heat transfer coefficients behind the quench front are calculated through coolant temperature obtained via new "cascade" algorithm. The result is a detailed map of heat transfer coefficients for all measured points (e.g. Fig.9).

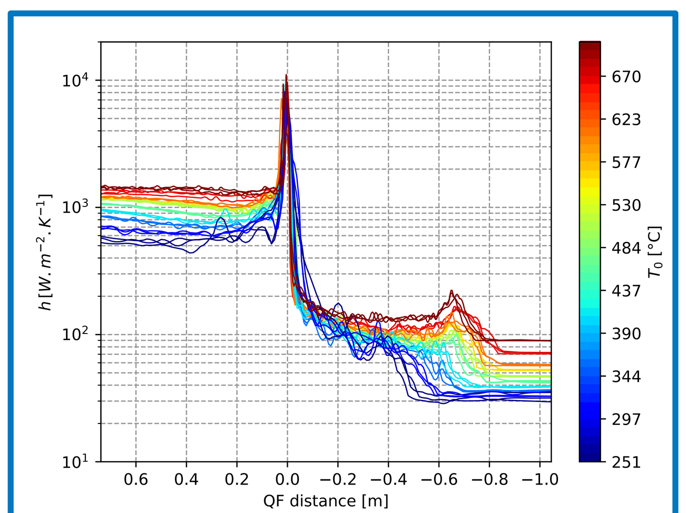


Fig.9: Heat transfer coefficients for model B

Quench front velocities

Quench front velocity is defined as a known pitch of two thermocouples overcome in a measured time interval (Fig.12). The quench front velocity mainly rises with lower initial wall temperature, lower quenching temperature and it decreases with thicker wall (Fig.13).

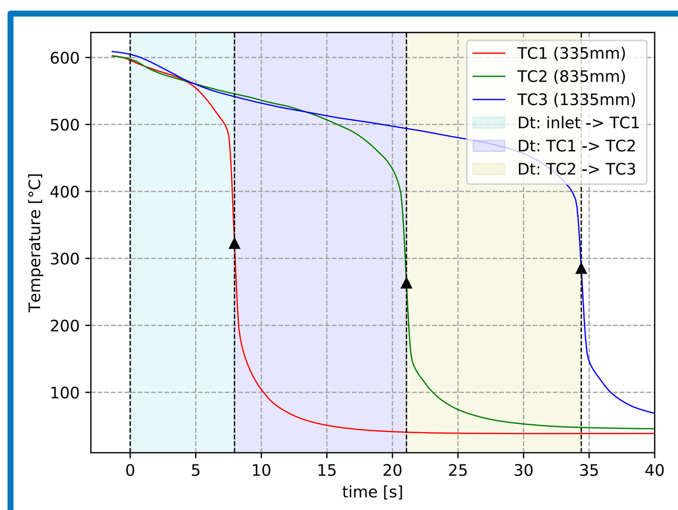


Fig.12: Temperature profiles and quenching intervals

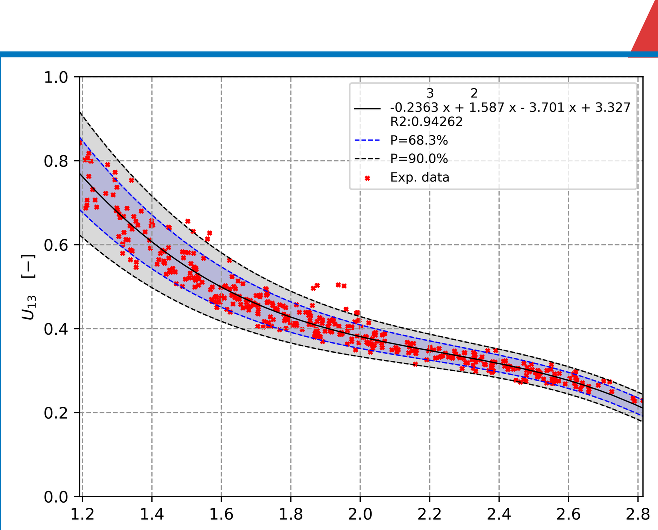


Fig.13: Correlated quench front velocity data

Conclusions

The presented experimental study was focused on the rewetting phenomenon in the annular channel with bottom flooding configuration. Over 400 experiments were performed in order to obtain sufficient information about the process. The most important results are solutions for quenching and nucleate boiling temperatures, which are accompanied by correlations for heat transfer coefficients in the main individual points and regions along the flooded geometry. Quenching temperature correlation is also main input for the solution of quench front velocity prediction. A surprising finding related to quench front velocity is, that relative front velocity to inlet velocity of the coolant is not dependent on actual flow rate. It follows that the percentage inlet velocity value can be calculated only through initial wall temperature, quenching temperature, and wall thickness. The set of correlations developed in this study showed good agreement with acquired experimental data through all models and initial parameters (Fig.14).

Fulfilled Goals

- New experimental loop with changeable 1.7 m high test section
- New experimental data for a wide range of initial wall temperatures, flow rates, and wall thickness
- Set of new, fully automated scripts for data processing, with custom-built correlation script
- Improved detection of important temperature points and data approximation/filtration
- Heat transfer coefficients for every measured point throughout the time-spatial scale
- Correlations for HTC at important temperature points (quenching, critical heat flux, nucleate boiling)
- Correlations for HTC within each region between important temperature points
- Correlations for quenching and nucleate boiling temperature
- Suggestion of three regional rewetting model
- All-embracing quench front velocity correlation
- Pointed out the effect of pressure peaks
- Briefly described the effect of spacers

References

[1] A.K. Saxena, V. Venkat Raj, and V. Govardhana Rao. "Experimental Studies on Rewetting of Hot Vertical Annular Channel" In: Nuclear Engineering and Design 208 (2001), pp. 283–303.

Author's publications related to the Study

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