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# Transient boiling of water under exponentially escalating heat inputs. Part II: Flow boiling

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ABSTRACT

This paper presents an investigation of forced convection effects on transient boiling heat transfer of water on plate-type heaters, at atmospheric pressure, under exponentially escalating heat fluxes. It complements the work performed under pool boiling conditions presented in the companion paper (Part I). Infrared (IR) thermometry and high-speed video (HSV) were used to gain insight into the physical phenomena and generate data that can be used for development and validation of accurate models of transient flow boiling heat transfer. Exponential power escalations with periods in the range from 5 to 500 ms, and subcooling of 10, 25 and 75 K were explored. The Reynolds number was varied from 25,000 to 60,000, depending on the subcooling. Single-phase heat transfer, onset of the boiling driven (OBD) heat transfer regime and overshoot (OV) conditions were identified. The experimental data suggest that during the single-phase heat transfer regime, forced convection is the dominant heat transfer mechanism for long periods, whereas transient conduction is more important for short periods. A criterion based on the normalized time scale for turbulent heat transfer is shown to capture all single-phase heat transfer data on a single curve. At a given period, OBD heat flux and wall superheat, as well as OV wall superheat increase with increasing subcooling and increasing Reynolds number. For a given Reynolds number and a given subcooling, they decrease with increasing periods at short periods, when the dominant heat transfer mechanism is transient conduction, whereas they barely change for long periods, as the dominant single-phase heat transfer mechanism is forced convection. Once boiling is fully developed, the heat transfer coefficient is proportional to the wall superheat to the fourth power and increases with increasing subcooling.



## 1. Introduction

Most investigations on transient boiling of water under exponentially escalating heat inputs have focused on pool boiling conditions [1–7]. Forced convection effects have nonetheless been investigated in a few studies, with both ribbon [8,9] and wire heaters [10]. Soliman and Johnson [8] focused on the single-phase heat transfer regime, investigating the role of forced convection using a ribbon heater made of Deltamax® (50% nickel, 50% iron). They found that for short periods, much smaller than the travel time of the fluid in the heated channel ($L_h/V_b$), an estimate of the average wall temperature rise could be obtained by a one-dimensional transversal conduction model combined with a one-dimension longitudinal advection model.

Using a similar experimental apparatus, Johnson [9] reported that for stagnant water or low velocity, a reasonably accurate estimate of the single-phase heat transfer coefficient could be obtained with the transient conduction analytic solution reported by Rosenthal [1], whereas for higher velocities, a steady state forced convection coefficient for turbulent flow should be used. Johnson observed that boiling inception superheat decreases for increasing period and pressure for both pool boiling and low velocity conditions, whereas for higher velocity, a lower boiling inception superheat was surprisingly reported for higher subcoolings. In fact, these experimental data show considerable scatter and fail to give accurate quantitative information about the effect of period, velocity and subcooling on the transient boiling characteristics. No major differences with respect to steady boiling were observed for the fully developed nucleate boiling regime for periods of 5 ms or longer.

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| $a$ | thermal diffusivity [$m^2/s$] |
| $Cp$ | specific heat [J/kg K] |
| $D_h$ | hydraulic diameter [m] |
| $\Delta T$ | temperature difference [K] |
| $E_e$ | entrance effect [–] |
| $Fo$ | Fourier number (=$a\tau/L^2$) [–] |
| $h$ | heat transfer coefficient [W/mK] |
| $\bar{h}$ | normalized heat transfer coefficient [–] |
| $k$ | thermal conductivity [W/mK] |
| $L$ | thickness [m] |
| $P$ | pressure [Pa] |
| $Pr$ | Prandtl number [–] |
| $q''$ | heat flux [$W/m^2$] |
| Re | Reynolds number [–] |
| $t$ | time [s] |
| $T$ | temperature [K] |
| $u$ | velocity [m/s] |
| $V$ | velocity [m/s] |
| $z$ | spatial coordinate [m] |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | thermal effusivity [$W\sqrt{s}/m^2K$] |
| $\rho$ | density [$kg/m^3$] |
| $\tau$ | exponential period [s] |
| $\bar{\tau}$ | normalized period [–] |
| $\tau$ | shear stress [Pa] |

*Subscripts*

| | |
|---|---|
| 0 | initial |
| a | ambient |
| adv | advection |
| b | bulk |
| c | conduction |
| fc | forced convection |
| h | heater (ITO) |
| ito | Indium Tin Oxide |
| s | substrate |
| vor | turbulent vortex |
| wall | wall |
| w | water or wall |

*Superscripts*

| | |
|---|---|
| + | non-dimensional |
| * | shear |

*Acronyms*

| | |
|---|---|
| CHF | critical heat flux |
| FDNB | fully developed nucleate boiling |
| IR | Infrared |
| IRC | IR camera |
| ITO | Indium–Tin oxide |
| HSV | high-speed video |
| OBD | onset of boiling driven regime |
| ONB | onset of nucleate boiling |
| OV | overshoot |
| PG | pressure gauge |
| PT | pressure transducer |
| RTD | resistance temperature detector |

Kataoka et al. [10] investigated the effect of forced convection on a platinum wire heater. For the single phase heat transfer coefficient, they found results consistent with those obtained by Johnson et al. [8,9]. Two types of transient boiling curves were observed. In most cases, the transient boiling curve at high heat flux coincided with the steady, fully-developed nucleate boiling curve and/or its extrapolation (called A-type). For a few cases, the wall superheat remained higher than the FDNB curve until the maximum heat flux was reached (called B-type). In A-type curves, the maximum heat flux reached during the exponential power escalations increased with decreasing periods, increasing pressure, velocity and subcooling.

The purpose of this work is to improve the understanding of forced convection effects on transient heat transfer and extend to forced flow the analysis of pool boiling transient heat transfer presented in the companion paper [11]. Exponential power escalations with periods in the range from 5 to 500 ms, and subcooling of 10, 25 and 75 K were explored. The Reynolds number was varied from 25,000 to 60,000. The same diagnostics used in the pool boiling investigations [11] were adopted.

## 2. Description of the flow boiling facility

Flow boiling tests were performed in the flow loop shown in Fig. 1 [12,13]. It consists of a variable frequency pump, flow meter, temperature and pressure instrumentation, preheater, flow channel with the test section, heat exchanger, accumulator and a fill and drain tank.

The flow channel consists of three parts: two 316 L stainless-steel sections and a quartz test section, as shown in Fig. 2. Each section has a rectangular flow area of 30 mm × 10 mm (300 $mm^2$). The two stainless-steel sections are located upstream

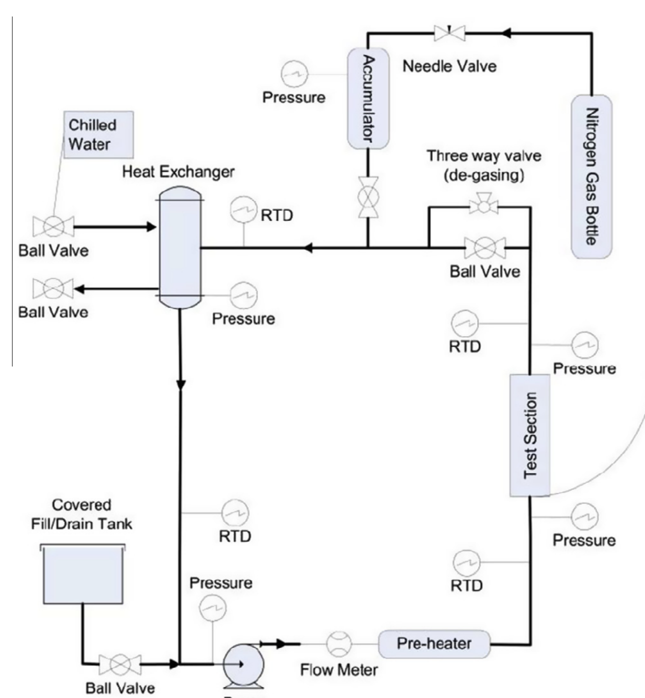


**Fig. 1.** Sketch of the MIT/NSE flow boiling apparatus (figure from [12]).