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Battery thermal management by boiling heat-transfer

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ABSTRACT

In this study, the ability of a boiling process to thermally condition (homogenisation *and* cooling) batteries is investigated. Thereto, a series of experiments are performed and discussed. Subjects that are treated are the dielectric property of the proposed cooling fluid, its cooling capability compared to that of air, the ability of the boiling fluid to thermally homogenise a battery and the influence of pressure variation on the boiling process. It turns out that the proposed cooling fluid conducts no electricity, has good cooling characteristics compared to those of air and, when boiling, is able to thermally homogenise the battery. Furthermore, pressure variation seems to offer a good method to regulate the boiling process.

1. Introduction

The development of electric vehicles (EVs) has undergone major breakthroughs over the last decade. Further improvement of EVs can be found in increased battery performance and more efficient energy schemes. Because the battery-pack durability and life also affect the cost and reliability of the vehicle, any parameter that affects this battery lifetime must be optimised. Temperature (range and uniformity) has a strong influence on the battery (pack) lifetime and thus on the overall performance of EVs [1,2]. With respect to temperature, the battery can be better conditioned compared to current EVs, where batteries are often passively cooled. Operation at elevated temperatures can seriously accelerate battery deterioration [3]. On the other hand, operation at lowered temperatures can seriously decrease the efficiency of the battery [4]. Hence maintaining a narrow temperature window can greatly benefit battery performance and lifetime.

Another important parameter affecting the battery lifetime is the temperature uniformity of the battery. If the cells and modules in the pack are at different temperatures, each module will be (dis)charged slightly differently during each cycle. After several cycles, modules in the pack will become unbalanced, degrading the packs performance [5]. Hence, especially in consideration of cycle life of the battery pack, a thermal management (homogenisation *and* cooling) scheme is indispensable [6].

Comparable thermal issues in high-end electronics are faced with advanced thermal management schemes based on boiling heat-transfer [7–9]. That is, thermal homogenisation as well as cooling is attained very effectively by heat exchange of the device with a boiling medium. Boiling heat-transfer namely affords cooling capacities substantially beyond that of conventional methods. It furthermore, allows for thermal homogenisation very effectively as it, irrespective of heat fluxes, happens at a fixed temperature for a given pressure [10,11]. As such, boiling heat-transfer thermal management can also solve problems that are currently arising in Boeing's 787 Dreamliner batteries [12].

Pool boiling may serve as physical representation for heat-transfer applications based on boiling heat-transfer. In thermal management schemes based on pool boiling, it is of importance to keep the system in the desired boiling mode. This is explained in more detail in Section 2. Due to fluctuating and uncertain heat-transfer demands this is a challenging task. Therefore, the boiling process in these thermal management schemes must be regulated. Controllers that achieve this are to be developed using theoretical models describing the dynamics of these systems.

However, to date, theoretical studies for pool boiling applications are scarce. Many publications on boiling experiments can be found on the other hand (see e.g. [13–15] for an extensive review). The boiling process is influenced by numerous variables, such as fluid-heater combination, surface roughness and system pressure. Consequently, experimental results can only be used in a very limited range of boiling applications. Theoretical investigation of pool-boiling systems may be found in [16–19]. Application

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of phase-change heat-transfer for thermal conditioning of battery packs in EVs can be found in [20,21,11].

Aim of the present study is the experimental investigation of the ability of pool boiling for thermal conditioning of batteries in EVs. First exploratory experiments are carried out to investigate:

- The electric interaction between battery and cooling fluid, i.e. the boiling liquid.
- The cooling capacity of the proposed cooling fluid.
- The ability of the boiling process to thermally homogenise batteries.
- The controllability of the boiling process.

In order to treat the first item, the dielectric property of the cooling fluid is investigated as no interaction between battery and fluid is desired. Items 2 and 3 are investigated using charge–discharge experiments. Finally, the influence of pressure variation on the boiling process is investigated to discuss the controllability of the boiling process. In this way, the principle of thermal homogenisation via the boiling process in a pool-boiling system is addressed for application in EVs.

This paper is organised as follows. In Section 2 additional background information with respect to pool boiling is given. Section 3 treats the experimental setups. In Section 4 the dielectric property of the proposed cooling fluid and its cooling capability are considered. Furthermore, the battery is pulse-charged–discharged to induce boiling and the thermal homogenisation of the battery is examined. The experimental results are compared to the evolution of a thermal battery model and the influence of the boiling process on the heat-transfer coefficient from battery to liquid is discussed in this section. Finally, the ability to actively and rapidly control the boiling process via regulation of the pressure in the boiling chamber is considered in this section. The findings are summarised and conclusions are drawn in Section 5.

2. Boiling as physical mechanism for thermal battery management

Pool boiling may serve as physical representation for thermal-conditioning applications based on boiling heat-transfer. Such systems consist of a heater submerged in a pool of liquid. The to-be-cooled device supplies heat to the bottom wall of the heater, which corresponds with a thermally conducting element between the actual heat source (e.g. the battery) and the coolant above the heater. The coolant can be chosen to be a dielectric fluid so as to eliminate the risk of short circuiting, which is essential in the case of batteries. As a result, no additional sealing between electrical circuit and coolant is required. The liquid extracts heat from the heater and eventually starts to boil and releases thermal energy through the escaping vapour. The vapour turns into liquid again in a condenser, releasing its heat, and flows back towards the boiling liquid.

Convection is the first mode of heat-transfer that occurs when increasing the heat flux (q) at the heater surface (initially at the saturation temperature of the cooling fluid) which is represented by region I in Fig. 1. Further increasing the heat flux results in an increased heater temperature and at some point (A in Fig. 1) bubbles begin to appear randomly on the heater surface. This is the onset of partial nucleate-boiling (region II). Continued increase of the temperature and heat flux causes the merger of the isolated vapour bubbles into jets of vapour. This transition (point B) marks the beginning of the fully developed nucleate-boiling regime, corresponding with region III in the figure. In this regime the departed bubbles leave a tiny dry spot in the liquid on the heater surface, and upon further increasing the heater temperature, more and more dry spots are formed. Due to the lower heat-transfer

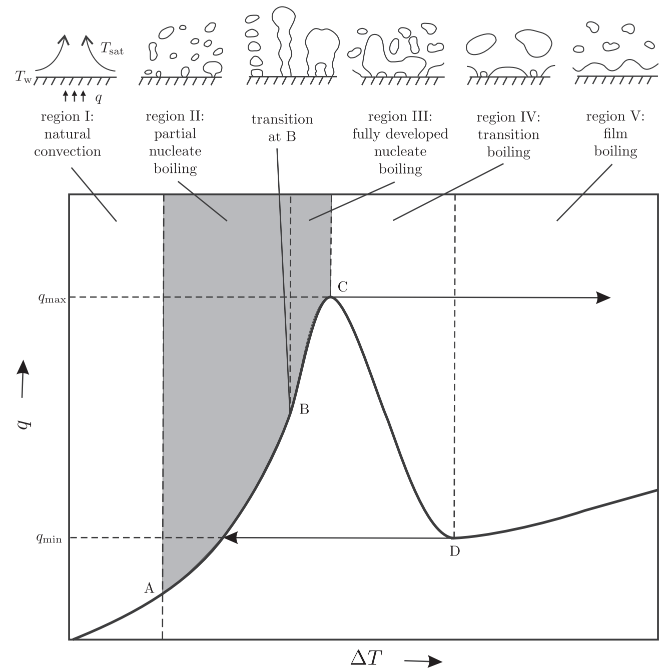

Fig. 1. Typical boiling curve, showing qualitatively the dependence of the interface heat flux (q) on the surface superheat (ΔT), defined as the difference between the surface temperature and the saturation temperature of the liquid. The various regions characteristic for boiling processes are indicated ([13]).

coefficient of vapour compared to liquid, this thermally insulates the heater. At some point (C in Fig. 1) the high heat fluxes can not be accommodated anymore by nucleate-boiling and the system enters the transition-boiling regime (region IV). The heater is rapidly covered with more and more vapour. As a result of the insulating vapour spots on the heater, its temperature rises very rapidly. Since this increase in temperature is accompanied by a reduction in heat flux, the transition regime is highly unstable. At point D in Fig. 1, the heater surface is covered by a global vapour film and the stable film-boiling regime (region V) is entered. If the heat supply remains constant, the system temperature will increase to the point where the same heat flux is generated for a solid–gas contact, this is accompanied by a massive increase in temperature.

In thermal homogenisation schemes, the desired mode of boiling is nucleation boiling, corresponding with region II and III in the figure. Here the slope of the boiling curve corresponds to heat-transfer coefficient. Higher heat-transfer coefficients thus indicate a more violent mode of boiling. Furthermore, the characteristic time scale of the temperature evolution scales with the inverse of the heat-transfer coefficient, meaning a more violent mode of boiling allows for (much) quicker responses to changing heat-transfer demands, due to the dynamical power requirements in EVs. Operation temperatures close to point C thus are desired in thermal management schemes for EV-batteries.

3. Laboratory set-up

The ability of thermal homogenisation of a battery-pack via boiling heat-transfer is investigated by a series of exploratory experiments. In this study, it is examined whether boiling can indeed thermally homogenise 1 Ah Li-ion batteries (Sony US18500VR, dimensions: diameter = 18 mm, height = 49 mm) and whether the boiling process can be influenced via the pressure in the boiling chamber. The proposed cooling fluid is Novec7000 (3M, USA, chemical composition: 99.5 weight percentage of $C_3F_7OCH_3$