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Precision cooling for CO_2 reduction

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Abstract

Global climate is adversely affected by increasing emissions of carbon dioxide and other green-house gases. The road transport sector contributes significantly to these emissions. Irrespective of the source of energy– Internal Combustion Engines (ICEs) or electric motors, cooling is an important factor that affects the operating performance and more importantly, the efficiency. Efficient cooling positively impacts operating efficiency by reducing fuel consumption and thereby leads to reduced CO_2 emissions. The high power density of modern day ICE causes excessive thermal loads to be exerted on the engine components. This reiterates the demand for efficient cooling. While the convectional cooling system grows in size, it also extracts more power from the engine output. It is, therefore, desired to provide efficient cooling of the hot spots, while avoiding over-cooling of the regions with low or moderate temperature. This method, known as precision cooling, improves local cooling and minimizes overall cooling. This in turn reduces the heat losses and thereby improves the thermodynamic efficiency of the ICE.

Local boiling can be an efficient way to implement precision cooling. The heat transfer involving nucleating and collapsing vapor bubbles near the surface of a hot metal is known as nucleate boiling. This phenomenon can positively impact cooling, as a significant amount of heat is extracted from the hot metal for the evaporation of the coolant to its vapor phase. Thus, heat is efficiently transferred locally near the hot spot through the vapor bubbles. However, excessive boiling could be counter productive and can lead to formation of a thin vapor film with low thermal conductivity on the metal surface. This film reduces heat transfer, prevents cooling and can eventually lead to material breakdown. Hence, it is extremely important to use nucleate boiling without the risk of having film boiling. Therefore, accurate estimation of boiling heat flux is the first step towards utilizing the potential of nucleate boiling. The main focus of this work is on numerical models to estimate the wall boiling heat flux. Such numerical models can be used in conjunction with Computational Fluid Dynamics (CFD) to analyse the heat transfer inside an ICE coolant jacket. A semi-mechanistic boiling model, based on established existing models in literature, has been proposed. Experiments performed on simplified geometries, representative of the areas in the ICE where boiling can be encountered, are used for validating the new model. The results from the validation study show that boiling is affected by properties of the flow, fluid and the solid. In addition to an improvement in accuracy of predicting the boiling heat flux, the model also provides a conservative measure to limit boiling and ensure the adverse effects of excessive boiling are not encountered. Finally, the limitations in the current model are discussed along with a possible solution for improvement.

Keywords: subcooled flow boiling, boiling regimes, active nucleation site density, semi-mechanistic models, internal combustion engine, coolant jacket

to my family

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Sudharsan Vasudevan
Göteborg, December 2019

List of abbreviations

Abbreviations

CFD	–	Computational Fluid Dynamics
ICE	–	Internal Combustion Engine
ONB	–	Onset of Nucleate Boiling
CHF	–	Critical Heat Flux
FDB	–	Fully Developed Boiling
BDL	–	Boiling Departure Lift-off

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Vasudevan S., Etemad S., and Davidson L. "Improved Estimation of subcooled flow boiling heat flux for automotive engine cooling applications". *ASME-JSME-KSME 2019 8th Joint Fluids Engineering Conference, AJK-Fluids2019, July 28-August 1, 2019, San Francisco, CA, USA*. ASME (in press)
Paper B	Vasudevan S., Etemad S., Davidson L., and Villar G.M. "A blended model to compute heat transfer in subcooled flow boiling". *Technical report*

Contents

Part I
Extended Summary

Chapter 1
Introduction

Emission of green-house gases has a direct effect on the global climate. Carbon dioxide (CO_2) equivalent is a commonly used measure to compare the emissions from various green-house gasses. To compute CO_2 equivalent, the amounts of other gases are converted to equivalent amount of carbon dioxide based on their respective global warming potential. Transport sector is one the major contributors to these emissions. In Sweden, domestic transportation contributes, on an average, to 30% of total CO_2 equivalent emissions [3]. Of this, the contribution from the road transport sector is the highest, accounting for 15497 kt CO_2-eq of the 16590 kt CO_2-eq (year 2017). The unit kt CO_2-eq stands for kilo tonnes of carbon dioxide equivalent. Figure 1.1 shows the emission data of green-house gases from road vehicles in Sweden.

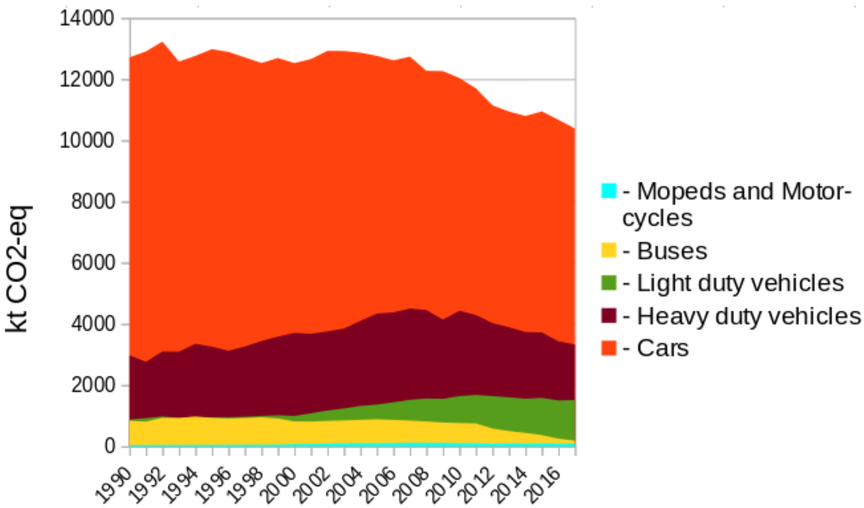


Figure 1.1: *Emission of green-house gases from road vehicles in kt CO_2-eq, considering only domestic transport. Obtained from statistikmyndigheten SCB (1990-2017) [3]*

Though, there has been a consistent effort in mitigating emissions since 1990, the effect of emissions on the climate is becoming a topic of serious concern in the recent years. This is also evident from Figure 1.1, where a desperate attempt at minimizing emissions can be seen in the period between 2012 and 2017. Further, the advent of electric propulsion in road vehicles (battery electric vehicles and vehicles with hybrid propulsion) is a promising technology towards minimizing emission of green house gases.

Regardless of the source of energy for propulsion, cooling is an indispensable part of the automotive driveline in order to protect components experiencing critical temperatures.

However, over cooling or cooling of the regions which do not exceed critical temperature is a waste of energy. Excessive cooling of non-critical zones decreases the engine's thermodynamic efficiency. This in turn leads to increased fuel consumption and results in increased CO_2 emissions.

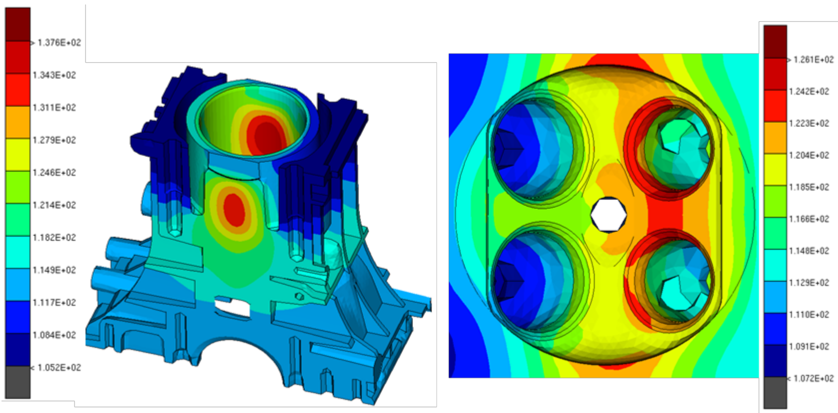


Figure 1.2: *Temperature distribution obtained numerically, from the work of Etemad et al.[4] showing an ICE– cylinder block (left) and cylinder head (right). The distribution is clearly non-uniform with prominent local hotspots.*

Narrowing down the scope of this discussion to Internal Combustion Engines (ICEs), a recent trend in increasing specific power— the ratio of power to stroke volume– is realized. This trend is predominantly a result of consistent effort to downsize engines for (a) improving fuel efficiency (b) accommodating an electric driveline— hybridization and (c) increasing the load carrying capacity (in case of heavy duty vehicles). Hence, engines have become smaller and the number of cylinders have been reduced, resulting in increased power density. Consequently, the engine structure experiences higher thermal loads. Figure 1.2 shows the temperature distribution on an ICE from the work of Etemad et al [4].

A conventional cooling system with a large cooling fan and pump is a parasitic load on the engine power output. The cooling packages and the cooling fans have already reached a size that challenges the spacial constraints in vehicles. Further, speeding up the coolant pump is often associated with cavitation problems. Also, since the fan power consumption is proportional to the cube of its operating speed, the fan consumes a significant portion of the additional power output from the engine. Therefore, an effective cooling system governed by an efficient strategy for cooling is an absolute necessity. In line with this discussion, the first strategy in designing such a cooling system is to minimize overall cooling and improve local cooling. This approach is commonly known as precision cooling.

The temperature of critical components in the engine structure can often exceed the liquid saturation temperature. In such conditions, the occurrence of boiling is encountered. Local boiling is an efficient way of precision cooling. Vapor bubbles nucleate from the hotspots on the metal surface, get transported by the liquid coolant which is at a relatively much lower temperature and finally collapse into the bulk of the liquid. This phenomenon is known as nucleate boiling. A significant amount of heat is required for the evaporation of the coolant to its vapor phase and this heat is extracted from the hot metal. In essence, the vapor bubbles effectively transfer heat from the hot metal surface to the liquid coolant. Hence, the heat transferred by nucleate boiling is enhanced compared to the one by single phase forced convection– where the liquid coolant flows over the hot surface without undergoing any phase change. Further, reduction of coolant flow rate enables more intense nucleate boiling. However, too much boiling can lead to merging of large number of vapor bubbles into a thin vapor film. This film has a low thermal conductivity and reduces heat transfer and thereby negatively affects cooling. Therefore, controlled nucleate boiling ensures selective efficient cooling of local hotspots and minimized excessive cooling of non-critical regions or in other words, promotes precision cooling.

Precision cooling also aids in increased operating temperature of the engine during warm-up conditions and low load operations. In these scenarios, rejecting the excess heat from the combustion process is not the desired option. Increased operating temperature also causes reduction in viscosity of the lubricating oil and thereby minimizes energy lost to friction. Additionally, the coolant is accessible at a higher temperature and this could help in improving the performance of the heat exchangers such as radiator and cab heater. Thus, precision cooling also has an overall positive impact on complete vehicle thermal management.

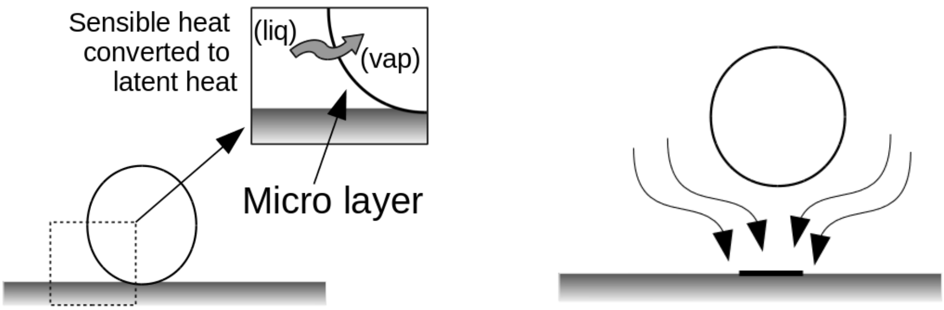
Aim

The focus of this work is on developing methods for enhancement of the local cooling, particularly in the most sensitive regions of the engine coolant jacket. The opportunities in utilizing the potential of nucleate boiling are explored and the adverse effects of excessive boiling is realized as a serious limitation. In line with this, the following are stated as objectives for this work.

- To evaluate existing numerical wall boiling models and understand their limitations.
- Develop an improved boiling model that can be used in conjunction with CFD for the application of engine cooling.
- Validate the new model with relevant experimental data in literature.

Chapter 2
Theory

Nucleate boiling can be classified into pool boiling or flow boiling based on nature of convection in the liquid/coolant. It is said to be pool boiling if the flow involves only natural convection and flow boiling if the convection is forced. Flow boiling can further be classified into subcooled or saturated, based on whether the bulk temperature of the liquid is less than or equal to its saturation temperature. Subcooled flow boiling is relevant to the scenario in an engine coolant jacket. As mentioned earlier nucleate boiling is an effective mode of heat transfer. This effective heat transfer is predominantly governed by two mechanisms– micro-layer evaporation and quenching of the hot metal post bubble departure. Sensible heat from the hot metal is conducted to the liquid in the immediate vicinity of the metal surface. As a result of the surrounding superheated conditions, vapor bubbles nucleate from gases/vapor trapped in small crevices and cracks on the metal surface, referred to as bubble nucleation sites. These vapor bubbles grow in size and are fed by a thin liquid layer adjacent to it, as illustrated in Figure 2.1a. In this thin layer, known as the micro-layer, the sensible heat is converted to the latent heat required by the vaporization process. This mechanism is known as micro-layer evaporation. Further, the flow transports these bubbles into the bulk of the liquid coolant, where they collapse and condense back to the liquid phase. This ensures the effective heat transfer from the metal to the coolant through the vapor bubbles. On the other hand, once a bubble leaves the metal surface, the hot bubble nucleation site is quenched by the subcooled liquid which fills the space created by the departed bubble. This mechanism is illustrated in Figure 2.1b.



(a) *micro-layer evaporation* (b) *quenching of hot metal post bubble departure*

Figure 2.1: *Mechanisms governing effective heat transfer in nucleate boiling*

While nucleate boiling is an efficient mode of heat transfer, it is a complex phenomenon that involves simultaneous presence and interaction of multiple phases. Various regimes of subcooled flow boiling can be identified based on the vapor bubble population and their interactions. These regimes are encountered by increasing the wall temperature.

The variation of heat flux with wall temperature can be represented in what is known as a boiling curve. Figure 2.2 represents a qualitative boiling curve, showing the behaviour of heat flux for different boiling regimes.

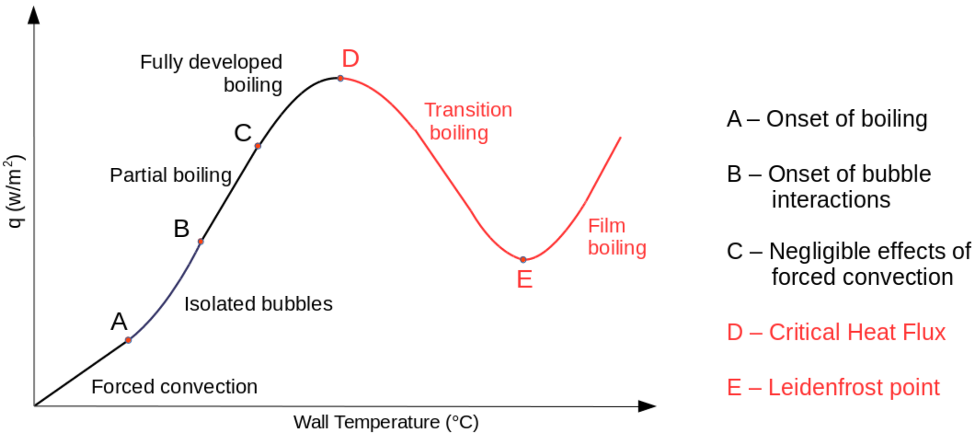


Figure 2.2: *Qualitative boiling curve showing the variation of wall heat flux with wall temperature for different boiling regimes encountered in subcooled flow boiling*

Initially, when the wall temperature is below the saturation temperature, the flow is within the single phase forced convection regime. The first bubble appears when the wall temperature is a few degrees above the liquid saturation temperature. This marks the Onset of Nucleate Boiling (ONB). After ONB, the bubble population steadily increases with increasing wall temperature. The vapor bubbles constantly nucleate and collapse. During the initial stages of boiling, the vapor bubbles are independent and do not interact with each other. This regime of boiling is known as the isolated bubbles' regime. However, with increasing wall temperature, the vapor bubbles increase in number and start interacting with each other. Increase in boiling results in minimizing the effect of forced convection on heat transfer. At the farther end of this spectrum the intensity of bubble interactions is quite high and the effect of forced convection on the heat transfer becomes almost negligible. This regime of boiling is known as fully developed boiling (FDB). The intermediate regime, in between the isolated bubbles' and FDB, is known as partially developed boiling regime. Any further increase of wall temperature beyond the FDB regime leads to transition and film boiling regimes. These regimes are characterized by merging of the interacting vapor bubbles on the heated surface into a thin vapor film. This vapor film has low thermal conductivity and hinders heat transferred from the heated surface. This leads to cease of cooling and rapid increase in wall temperature. The maximum heat flux point beyond which the heat flux decreases is termed as Critical Heat Flux (CHF).

In addition to complexities involved in the phenomenon of nucleate boiling, the complicated geometry of the engine coolant jacket and lack of visual access into its critical regions are major challenges to this study. Hence, simplified representative geometries are used in this work the for study and validation of numerical models. Numerical models can be categorized into two types — empirical or semi-mechanistic. The empirical models are correlations of important fluid and flow parameters, developed based on large number of experimental data points. On the other hand, semi-mechanistic models are formulations based on dominant physical mechanisms and some empirical correlations to compute specific components and/or sub-components of the overall formulation. The numerical models used in the present study use the semi-mechanistic modeling approach. The scope for applicability of the semi-mechanistic models are usually restricted to specific boiling regimes. This is because the models are developed based on physical mechanisms specific to a particular boiling regime and therefore the accuracy of the models are questionable outside these regimes. Thus, predicting the heat transfer due to boiling over a wide range of boiling regimes using semi-mechanistic approaches is a gap to be bridged.

Chapter 3
Methodology

In the initial part of this work, two existing boiling models are evaluated– the Boiling Departure Lift-off (BDL) model introduced by Steiner et al [5] and Rohsenow's correlation [6]. These models are developed for different boiling regimes. The BDL model is applicable in the isolated bubbles' regime and Rohsenow's correlation is applicable in the Fully Developed Boiling (FDB) regime. A brief introduction to these models is presented below.

1. The BDL model formulates the subcooled flow boiling heat flux based on mechanics of an isolated vapor bubble. This involves computation of vapor bubble radii, which is calculated based on the balance of following forces acting on individual bubbles.

    - Drag
    - Lift
    - Unsteady-drag due to asymmetric bubble growth
    - Buoyancy

    While the drag, lift and buoyancy forces are self-explanatory, the unsteady drag force due to asymmetric bubble growth is the force exerted by the liquid on the vapor bubble as a result of the bubble growth itself. A complete description of the BDL model is presented in Part II. In addition to this, the derivation of the unsteady drag force due to asymmetric bubble growth is available in Part III.

2. Rohsenow's correlation is an empirical pool boiling correlation. In this work, the model is used to estimate the heat flux in the FDB regime. As mentioned previously, the conditions during FDB is similar to that of pool boiling, since the effect of forced convection on heat transfer is negligible. The correlation is presented in Part II.

Evaluation of the models resulted in identification of a scope for improving the accuracy of the BDL model. The formulation of the drag and lift forces are improved and the results are validated with experiments by Steiner et al [5]. This is discussed in Paper A of Part II.

The two boiling models are developed for different boiling regimes. Therefore, their applicability outside these regimes is questionable. The increase in bubble population and bubble interactions distinguish the isolated bubbles and FDB regimes. In this work, this increase in bubble population and bubble interactions is quantified and used to blend these two models. The new blended model estimates the boiling heat flux across different boiling regimes. This is introduced in Paper A and is validated with experiments by Steiner et al [5]. In Paper B, the performance of the new model is validated with results from four different, relevant experiments found in literature. Also, the advantages and limitations of the new model are identified and discussed.

Chapter 4
Concluding remarks

In this work, the idea of utilizing the potential of nucleate boiling for precision cooling of ICE is explored. Controlled nucleate boiling is a promising strategy for precision cooling. This way of cooling not only improves the thermodynamic efficiency of the engine, but also has a positive impact on overall vehicle thermal management. However, the first step towards utilizing the potential of controlled nucleate boiling is to understand the boiling phenomenon and estimate the boiling heat flux. This is achieved by evaluating the existing boiling models in terms of accuracy and applicability. As a result, the present work suggests the following two major improvements for predicting the boiling heat flux with improved accuracy.

1. Improved formulation of the drag and lift forces in the BDL model.

2. A mechanistic approach towards blending the BDL model and Rohsenow's correlation based on bubble interactions.

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where, b is a model constant which can be varied to curve-fit available experimental data and Ja is the Jakob number– the ratio of sensible heat to latent heat absorbed during a phase change process.

2 Derivation of expression for bubble radius as a function of time

Vaporization process in nucleate boiling is maintained by energy transfer from the superheated liquid to the bubble interface. The temperature drop maintaining this process is localized to a thin boundary layer which surrounds the bubble (shown in Figure 1).

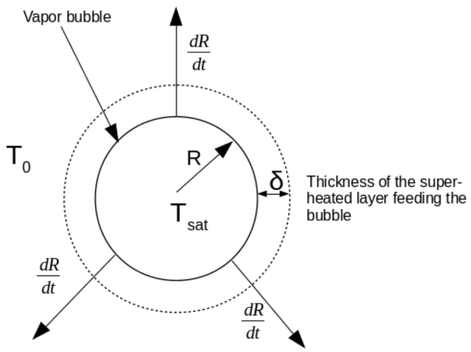

Figure 1: Thin layer of super heated liquid around the vapor bubble which feeds the bubble with vapor.

The energy balance for the theory discussed above is given by

$$h(T_o - T_{sat}) = h_{fg}\rho_v \frac{dR}{dt} \tag{14}$$

where, T_0 is the temperature of the superheated liquid surrounding the vapor bubble. For a uniformly superheated liquid, the physics involved in growth of a vapor bubble is analogous to a 1D transient heat conduction problem given by

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{15}$$

with conditions

$$t = 0: \quad T(x, 0) = T_0 - T_{sat} \tag{16}$$

$$t > 0: \quad T(0, x) = 0 \tag{17}$$

where, $x = 0$ represents the bubble-liquid interface. The solution for the above transient conduction problem reads

$$\left(\frac{\partial T}{\partial x}\right)_{x=0} = \frac{T_0 - T_{sat}}{\sqrt{\pi \alpha t}} \tag{18}$$

This conductive heat flux is assumed to be equal to the heat flux required for bubble growth at the liquid-vapor interface.

$$k\left(\frac{\partial T}{\partial x}\right)_{x=0} = h(T_0 - T_{sat}) \tag{19}$$

Further, Equation 18 gives,

$$k\frac{T_0 - T_{sat}}{\sqrt{\pi \alpha t}} = h(T_0 - T_{sat}) \tag{20}$$

and the vapor bubble growth rate is obtained by introducing the energy balance discussed previously in Equation 14.

$$k\frac{(T_0 - T_{sat})}{\sqrt{\pi \alpha t}} = h_{fg}\rho_v \frac{dR}{dt} \tag{21}$$

Integrating Equation 21,

$$R = \frac{2}{\pi} Ja \sqrt{\pi \alpha t} \tag{22}$$

$$Ja = \frac{\Delta T_{sat} c_{p,l}}{h_{fg}\rho_v} \tag{23}$$

In Equation 23, T_0 – the superheated temperature of the liquid in the vicinity of the vapor bubble is approximated as the wall temperature. Hence, the wall superheat term, ($\Delta T_{sat} = T_{wall} - T_{sat}$) appears in the expression for the Jacob number (Ja).