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PDF issue: 2026-08-11

High Heat Flux Boiling Heat Transfer and Its Application on Cooling System

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(Degree)
博士（工学）
(Date of Degree)
2011-03-25
(Date of Publication)
2011-11-09
(Resource Type)
doctoral thesis
(Report Number)
甲5307
(URL)
https://hdl.handle.net/20.500.14094/D1005307

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博士の専攻分野の名称　博士（工学）
学 位 記 番 号　　博い第 5307 号
学位授与の 要 件　　学位規則第 5 条第 1 項該当
学位授与の 日 付　　平成 23 年 3 月 25 日

【 学位論文題目 】

High Heat Flux Boiling Heat Transfer and Its Application on Cooling System（高熱流束沸騰熱伝達とその冷却システムに関する研究）

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(別紙様式 3)

論文内容の要旨

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専　攻 海事科学専攻

論文題目（外国語の場合は，その和訳を併記すること。）

High Heat Flux Boiling Heat Transfer and Its Application on Cooling System （高熱流束沸騰熱伝達とその冷却システムに関する研究）

指導教員 福田 勝哉

1. Introduction

Facing the escalation of anticipated heat dissipation requirements on the high-power electronic devices such as insulated gate bipolar transistor (IGBT) module onboard ship that is due to large implementation of electric propulsion drive (EPD) system and fully electric ship (FES) system, the improvements and also developments of new and reliable cooling techniques are highly required. Cooling the high-power electronic devices with heat dissipating more than 300 W/m^2 at the die is beyond the capability of the most conventional cooling by natural and forced air-cooling. The above motivation led to the series of investigations by experimental study on the high heat flux boiling heat transfer processes in terms of employing boiling for cooling. The investigations include the pool boiling and the fundamental two-phase flow boiling studies through the development of closed loop thermosyphon as a cooling device. About 2700 known data were derived and analyzed to observe the pool boiling phenomena and measure the critical heat fluxes by transient heating on horizontal heaters. Correct understanding of boiling heat transfer processes including two-phase flow boiling and its mechanisms in narrow channels and specified cooling systems can help engineers to design and evaluate heat generation systems.

2. Transient pool boiling heat transfer in highly wetting liquid FC-72

In this research, study of pool boiling heat transfer is focused on the investigation of critical heat flux (CHF) and its mechanisms in the transition to film boiling from nucleate boiling and also non-boiling convection and conduction processes in a pool of highly wetting liquid FC-72. The pool boiling was measured on the horizontal heater due to transient heating (exponentially increasing of heat rates ranging from quasi-steady to rapidly increasing ones), $Q_0e^{t/\tau}$, under a wide range of pressures ranged from sub-atmospheric to 1.082 MPa. The test heater was mounted horizontally inside boiling vessel and the controlled exponentially heat generation rate was given to the heater.

From the observations on steady-state heat transfer at periods above 10 s, it was observed that the steady-state CHFs are lower than the corresponding values of CHFs based on hydrodynamic instability (HI) model. The phenomenon exists from both measurements on horizontal cylinders and ribbon and was assumed due to HSN process in originally flooded cavities on solid surface without contribution of active cavities. However, the horizontal vertically oriented ribbon was reported to have a lower of increasing rate of CHFs than ones from horizontal cylinders (Sutopo, 2008). It was confirmed also that the transient CHFs due to exponentially increasing heat input remain a typical of CHF for period, and were separated into the first, second, and third groups for long, short, and intermediate period respectively. It was found that the CHFs from platinum and gold horizontal cylinder agree each other and higher than ones from ribbon in whole range of periods (Sutopo, 2008).

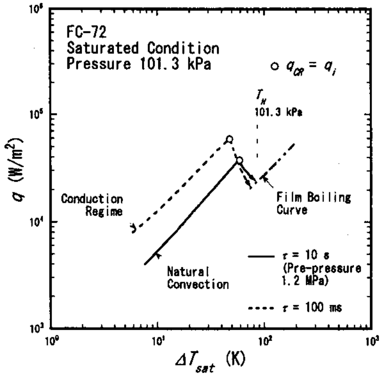


Fig. 1 Direct transition processes at periods of 100 ms and 10 s

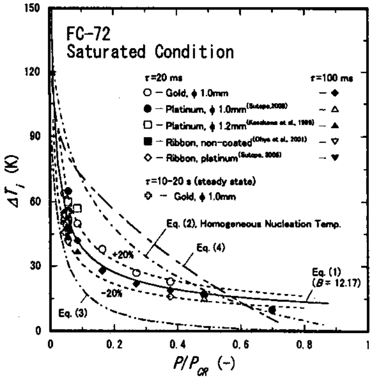


Fig. 2 ΔT_i vs reduced pressure

Investigations on the transition boiling process from non-boiling to film boiling include the observations on the three kinds of transition processes. One of the important mechanisms is the transition from heat conduction to film boiling induced by an explosive-like incipient boiling and then directly followed by critical heat flux involving a significant formation of film boiling through the dominance of the vapor film and surface contact. '*Direct Transition*' was named to this kind of process due to the directly process of heat transfer to the transition boiling after boiling incipience without nucleate boiling occurrences (Sakurai, 2000). Other authors have observed also this kind of transition in various liquid and heater configurations. (Sakurai et al., 2000)(Fukuda et al., 2000, 2004)(Kasakawa, 1999)(Ohya, 2001).

However, by quasi-steady-state heat transfer, it was observed that the direct transition also occurs from single phase natural convection at around atmospheric pressure and by the hydrostatic pressure, namely the pre-pressure, which is given to the heater surface prior to each experimental running. The typical direct transition processes either by conduction or natural convection on the horizontal cylinder heater in a pool of FC-72 due to transient heat inputs are shown in Fig. 1 for the log-log graphs of heat flux, q, versus surface superheat, T_{sat}. Both graphs were measured for short and long periods, 100 ms and 10 s, respectively. The direct transition was confirmed to exist due to the explosive-like heterogeneous spontaneous nucleation (HSN) during incipient boiling process in originally flooded cavities on surface. It was observed also that the direct transition from natural convection by quasi-steady-state increasing heat input at atmospheric pressure, gave the values of CHF 77% lower than ones in the case without pre-pressure from a fully developed nucleate boiling process.

$$\Delta T_i(\tau) = B\,(P/P_{CR})^{-0.5} \tag{1}$$

$$T_{sp} - T_{sat} \cong T_{CR}\left[0.923 - \frac{T_{sat}}{T_{CR}} + 0.077\left(\frac{T_{sat}}{T_{CR}}\right)^9\right] \tag{2}$$

$$\Delta T_{IBH} = T_{sat}(P_v) - T_{sat}(P) - C(q_i)^b\text{; where } P_v = P + \frac{2\sigma}{r} - P_{gas} \tag{3}$$

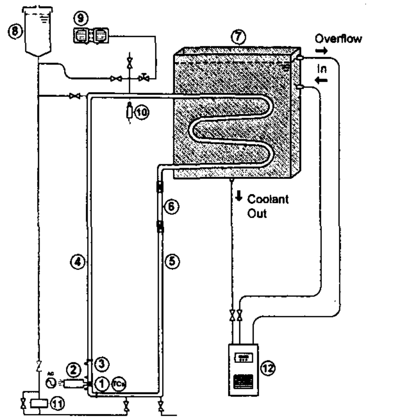
$$\Delta T_I = T_I - T_{sat}\text{; where } T_I = 0.92T_{CR}\left\{1 - 0.26\,e^{\left[\frac{-20(P/P_{CR})}{1+1700/P_{CR}}\right]}\right\} \tag{4}$$

The mechanism of direct transition is significantly influenced by the incipient boiling process and the CHF. In the current work, the incipient surface superheat required for inducing the direct transition process to film boiling by heat conduction process due to rapid increasing heat inputs was predicted by the empirical correlation in Eq. (1) based on experimental data. Figure 2 shows the data of incipient boiling surface superheat ΔT_i for short periods of 20 ms and 100 ms, and the corresponding correlation in a black solid line to express the non-linearly increase of the values that were measured for the reduced pressures, P/P_{CR}. The ΔT_i for short periods increases non-linearly with the decrease in reduced pressures and approaching the homogeneous nucleation temperature. These data were accompanied also for comparison by other measured data with transient heating from different horizontal geometries and materials of heaters. However, the incipient surface superheats seem to have less dependence on the exponential periods, τ, at each pressure. As seen in the figure, the corresponding curve almost agrees with the measured data, which are lying within an error range of ± 20%, with B=12.17. Other required models to predict the incipient surface superheat were also plotted in the graphs by correlations in Eqs. (2), (3), and (4), as suggested by Lienhard (1982), Bar-Cohen and Simon (1988), and Sakurai et al. (1990), respectively.

3. Performance of closed loop thermosyphon (CLT)

The fundamental flow boiling study was conducted through the development and application of two-phase closed loop thermosyphon for cooling high-power electronic semi conductors such as IGBT module in the frequency converter of EPD system. The experimental and analytical studies of the two-phase flow boiling cover several interest parameters which are required to design thermal systems and important for correct understanding the two-phase flow phenomena in a specified application. The current work is focused on the examination and analysis of the thermal performance of CLT and low pressure saturated water is considered as the working fluid.

Figure 3 shows the developed CLT set-up which mainly consists of evaporator, condenser and connecting tubes. The CLT set-up is a closed loop system with 600 mm in height, 2233 in length, and 220 ml total volume. Main loop is a copper pipe with inner diameter of 10.7 mm. Evaporator or heater is electrically heated and was made of a copper block with 1.01 mm diameter nineteen vertical circular channels in length of 20 mm and was drilled on the 12.6 mm diameter core body of the heater. Condenser is a simulated direct hull cooling method. It serves as a water-cooled condenser made of 12 mm thickness of steel plate with 300 mm × 250 mm surface area on the waterside.



(1) Evaporator or heater
(2) Hot copper block
(3) Glass tube
(4) Raising tube
(5) Falling tube
(6) PFA tube
(7) Condenser
(8) Feed tank
(9) Vacuum pump
(10) Pressure gauge
(11) Differential pressure gauge
(12) Circulation cooler

Fig. 3　Representation drawing of CLT set-up.

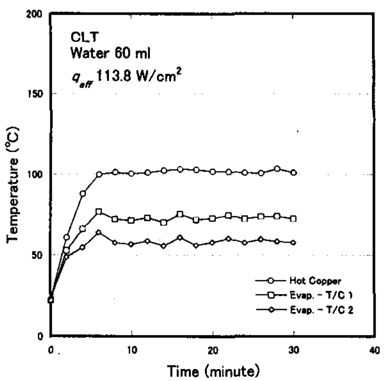


Fig. 4 Temperature profile of hot simulated component and evaporator at heat flux 113.8 W/cm² with 60 ml fill charge rate.

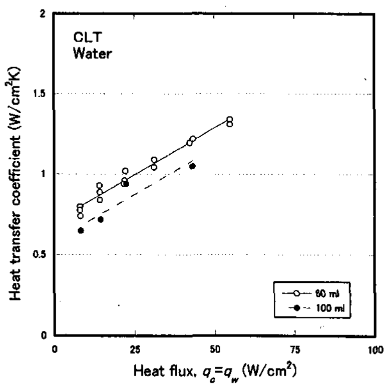


Fig. 5 Heat transfer coefficient vs. heat flux

Measurements were performed on all required parameters in response to the heat input from electrical heating by cartridge heaters. To calculate the experimental heat fluxes and the heat transfer coefficient, the attributed heat flux parameters are given by:

$$Q = V\frac{V_R}{R} \tag{5}$$

$$Q_{net} = Q - Q_{loss} \tag{6}$$

$$q_{eff} = \frac{Q_{net}}{A_{die}} \tag{7}$$

$$q_c = q_w = \frac{q_{eff} A_{die}}{nL\pi D} \tag{8}$$

$$h_{tp} = \frac{2q_w}{T_1 + T_2 - 2T_{sat}(z)} \tag{9}$$

In Fig. 4, it is seen that the CLT loop reach the stable running with balance of pressure to drive the flow. The fluctuations of temperature profile were suggested due to the effect of pressure losses along evaporator channel and the riser. It is shown also that system could reach the steady-state conditions as shown by steady temperature of evaporators and hot copper block at about 10-15 minute of waiting period after starting. This phenomenon was observed also in all measurements in different pressures and filling ratio. Figure 5 is the heat transfer coefficient measured for the process inside channels. The heat flux and the heat transfer rate were considered as the mean values assuming a uniform heat flux along channel and the axial distance of row channels. It is seen that the heat transfer coefficient increase almost linearly as the heat input increase. The flow boiling process in the channel could maintain the saturated condition and give heat dissipation process through channels configuration. However, the fill charge rate of 100 ml gave lower values than the 60 ml. It is considered due to the filling or flooding effect of top region of the riser of CLT.

4. Conclusions

A series of investigations on high heat flux boiling heat transfer on pool and flow boiling heat transfer have been performed. The results conclude several major items as follows:

(a) The transition of boiling heat transfer to film boiling in the pool boiling heat transfer in wetting liquid of FC-72 can be categorized into three kinds of mechanisms. They are mainly related to the kind of initial boiling process and nucleation process, and the transition to film boiling at CHFs.

(b) It was confirmed a new mechanism of boiling incipience in the pool boiling phenomena due to the explosive-like HSN.

(c) There are three groups of CHF for periods observed in the transient pool boiling CHF in FC-72. The CHF by direct transition in the quasi steady period were observed to exist with lower value of CHF than ones by fully developed nucleate boiling.

(d) The direct transition process has been investigated and the predictions related to the incipient boiling and the CHF due to rapid increasing heat input were derived.

(e) The CLT provides an efficient of heat transfer process in higher heat inputs rather than the lower ones. The subcooled inlet conditions and the back flow phenomena was observed in the lower heat input below about 350 W.

(f) CLT is suited for thermal management which could give self adjustment of pressure control and cooling process in response to the heat input to the heater.

(g) The flooding mechanism should be controlled to avoid the dryout or the CHF early on the high heat dissipation.

(h) Higher fill charge ratio might give lack of performance that was assumed due to flooding limitation.

(i) Heat flux and heat transfer coefficient is increase as the heat load increase in the system.

4. References

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（別紙１）　　　　　　論文審査の結果の要旨

氏名	Sutopo Purwono Fitri		
論文題目	High Heat Flux Boiling Heat Transfer and Its Application on Cooling System （高熱流束沸騰熱伝達とその冷却システムに関する研究）		
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要　旨

船舶の高出力化に伴い，船舶で使用されるパワーエレクトロニクス機器及び推進機器の冷却システムの構築は，重要な課題となっている。本研究では，電気推進を含んだ舶用機関システムの設計のみならず高集積半導体冷却システム等への応用に関連し，高熱流束冷却が可能な沸騰冷却及びその応用に資するためのデータ集積と沸騰熱伝達に関する基礎的な研究を行ったものである。まず，試験液体として電子機器冷却では一般的で代表的なフロリナート FC-72 を選択し，電力制御素子の過渡変化を想定して，発熱体に種々の速さの熱入力を与えたときの定常沸騰及び過渡沸騰特性について実験的検討を行い，広範囲の系圧力において，沸騰熱伝達特性及び過渡限界熱流束特性を明らかにしている。ついで，蒸発潜熱が大きく冷却能力の高い純水を利用し，電力制御素子の具体的な高熱流束冷却を想定したモデル二相閉ループサーモサイフォンを製作し，種々の熱入力に対して，熱輸送特性に及ぼす純水封入量の影響について明らかにしている。本論文は，６章から構成されている。第１章では，船舶における電力制御機器の冷却，沸騰熱伝達冷却及び閉ループ二相サーモサイフォンの基本原理を含めた冷却システムの背景について述べている。第２章で，本研究に関連するこれまで他の研究者らの行った研究成果の論文調査を丹念に行っている。第３章では，２つの実験装置及び実験方法について述べている。一つは，定常・過渡プール沸騰熱伝達実験装置及び方法であり，もう一つは，モデル二相閉ループサーモサイフォン実験装置及び方法である。FC-72 を利用したプール沸騰実験では，加熱制御装置および直流電源装置(700A)を用い，発熱率上昇速度(発熱率 e 倍時間)が 10ms～50s までの種々の速さで上昇させて実験を行い，非定常から準定常にかけての指数関数熱入力に伴う広範囲の系圧力およびサブクール度条件下(1.2MPa および 140K 程度)で，データを集積している。また，沸騰開始から限界熱流束に至るまでの沸騰現象の様相は高速度ビデオカメラ装置によって詳細に観察し，限界熱流束機構を映像的に検討した。純水を利用した二相閉ループサーモサイフォン実験装置は，高さ 600mm，流路全長約 2.2m 及び内容積は 220ml の自作の小ループである。重要な蒸発部は，多数の小径流路からなり効率よく熱交換できるように工夫されており，種々の熱入力に対する熱輸送特性実験を行った。第４章では，FC-72 について，種々の系圧力，サブクール度及び発熱率上昇速度の条件下の実験で得られた 2700 種類余りの沸騰曲線から，熱エネルギー変換の限界条件を明らかにした。特に，大気圧以下の低圧域から高圧域までの定常・過渡限界熱流束特性を明らかにしたことは，今後の機器の設計には有益であり，特筆に値するものであると考える。また，実験結果をまとめて，冷却システムの設計に必要な沸騰開始温度及び限界熱流束の予測実験式を提案している。第５章では，試作した二相閉ループサーモサイフォンによって得られた実験から熱輸送特性について検討し，良好な結果を得ている。最後に，第６章では，全体をまとめて結論としている。

本論文は，以下の５編の有審査論文により構成されている。

(1) Sutopo, P. F., Fukuda, K., Liu, Q.S., and Park, J., "Transient Pool Boiling Critical Heat Flux of FC-72 Under Saturated Conditions", ***JSME Journal of Power and Energy Systems***, Vol. 1 No.2, (2007) pp. 178-189.

氏名	Sutopo Purwono Fitri

(2) Sutopo, P. F., Fukuda, K., Liu, Q.S., "Transient Critical Heat Fluxes in Subcooled Pool Boiling of FC-72", *JSME Journal of Power and Energy Systems*, Vol. 2 No.2(2008), pp. 804-814.

(3) Sutopo, P. F., Fukuda, K., Liu, Q.S., "Direct Transition Phenomena in Pool Boiling of FC-72", *JSME Journal of Thermal Science and Technology*, Vol. 5 No. 2(2010), pp. 206-221.

(4) Sutopo, P. F., Fukuda, K., Liu, Q.S., "Transient Pool Boiling CHF in FC-72", Proceedings of 2008 ASME Summer Heat Transfer Conference, CD-ROM, HT2008-56272 (2008), pp. 1-17.

(5) Sutopo, P. F., Fukuda, K., Liu, Q.S., "Shipboard Thermal Management by Closed Loop Thermosyphon", Proceedings of 8th ***International Symposium on Marine Engineering*** (ISME BUSAN 2009), CD-ROM, Paper No.54 (2009) pp. 1-6.

本研究は，電気推進を含んだ舶用機関システムの設計，あるいは高集積半導体冷却システム等への応用に関連し，高熱流束冷却が可能な沸騰冷却及びその応用に資するためのデータ集積と基礎的な研究をおこなったものであり，今後，種々の熱エネルギー変換技術の発展のために重要な知見を得たものとして価値ある集積であると認める。

よって，学位申請者の Sutopo Purwono Fitri は，博士（工学）の学位を得る資格があると認める。