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HEAT TRANSFER COEFFICENT IN TWO PHASE COOLING SYSTEM OF THE SILICON DETECTORS IN THE ATLAS INNER DETECTOR PROJECT

WSPÓŁCZYNNIK PRZEJMOWANIA CIEPŁA W DWUFAZOWYM SYSTEMIE CHŁODZENIA DETEKTORÓW KRZEMOWYCH W PROJEKCIE ATLAS

Abstract

The two phase cooling system have been chosen for heat removal from Pixel and SemiConductor Tracker silicon detectors used in the ATLAS project at CERN laboratory. R218 was chosen as best coolant according to the requirements. Heat distribution on the cooling channel is not uniform and depends on detector's system design. There was presented new correlation to determine overall heat transfer coefficient for boiling flow in the small diameter horizontal pipe and non-uniform heat distribution.

Keywords: two phase flow, boiling, cooling and refrigeration system, R218-octafluoropropane

Streszczenie

Do odprowadzenia ciepła generowanego podczas działania detektorów krzemowych oraz elektroniki odczytu dla systemu Pixel i SemiConductor Tracker w projekcie ATLAS w laboratorium CERN wybrano układ przepływu wrzącego czynnika w kanale chłodniczym. Jako czynnik ziębniczy wybrano R218, który spełnia wymagania projektu. Na powierzchni kanału chłodniczego ciepło doprowadzane jest w sposób miejscowy i zależny jest od konstrukcji podsystemów detekcji. W pracy przedstawiono zależność umożliwiającą określenie wartości współczynników przejmowania ciepła dla przepływu wrzącego czynnika wewnątrz rur poziomych o małych średnicach i nierównomiernej dystrybucji ciepła.

Słowa kluczowe: wrzenie, parowanie, przepływ dwufazowy, systemy chłodnicze, R218-octafluoropropan

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1. Introduction

The Large Hadron Collider (LHC) is being built in a circular tunnel 27 km in circumference at the CERN Laboratory in Geneva, Switzerland. The tunnel is buried around 50 to 175 m underground. It is designed to collide two counter rotating beams of protons or heavy ions.

A Toroidal LHC ApparatuS (ATLAS) is one of the particle detectors installed on the LHC. The ATLAS is a particle physics experiment that will explore the fundamental nature of matter the basic forces that shape our universe. The ATLAS detectors will search for new discoveries in the head-on collisions of protons of extraordinarily high energy.

The Inner Detector (ID) measures the direction, momentum, and sign of charge of electrically-charged particles produced in each proton-proton collision. It consists of different sensor systems all immersed in a magnetic field parallel to the beam axis. The sensors closest to the collision point are the Pixel detectors. The Semiconductor Tracker (SCT) is the following. The gas based Transition Radiation Tracker (TRT) is a last part of Inner Detector. A mono-phase cooling system have been chosen for TRT sub-detector. This paper will not discuss the TRT [3].

2. Evaporative cooling system for SCT and pixel detecors

The silicon detectors and hybrids with electronic will produce around 48 000 W of heat, the thermal enclosures and service panels will produce 10 000 W. In total the cooling system must to remove around 60 kW of heat. The coolant mass flow must be as low as possible to minimize a total amount of structural materials to produce minimum background of secondary particles. The temperature of the silicon detectors should be kept around –7°C (this requirement applies to the fully irradiated detector and allows for minimizing the effect of the radiation damage and the detector to survive at least up to 10 years of operation). The cooling agent should be: non-corrosive, non-toxic and non-flammable. According to these requirements the evaporative cooling system have been chosen. The additional reasons why an evaporative cooling system is preferred over a mono-phase system are: the higher heat transfer coefficient between the coolant and the cooling block, the smaller temperature gradient along long cooling channel, the smaller size of the cooling system and thus lower coolant mass flows is due to the larger cooling capacity per unit volume in an evaporative system as result of vaporization [13].

The fluorocarbon C_3F_8 have been chosen as a cooling agent. Fluorocarbons are suitable for the cooling of SCT and pixel detectors because: high dielectric strength, good chemical stability under ionizing radiation, non-toxic, non-flammable, zero ozone depletion potential (ODP), high degree of compatibility with most of the metals, plastics and elastomers. Contrary to some classical refrigerants (HCFC or HFC) they do not contain hydrogen (under ionizing radiation HF acid may be formed so any H donor impurity must be absent).

Each cooling circuit consists of one recuperative heat exchanger, 1, 2 or 3 capillaries, detector structure, one heater on a return vapor line and piping connecting all the components to the distribution racks via one pressure and one back pressure regulator. Fig. 1 shows the cooling circuit scheme.

A functionality of the ATLAS ID evaporative cooling system is similar to that of a standard industrial fridge system and is presented on Fig. 2.

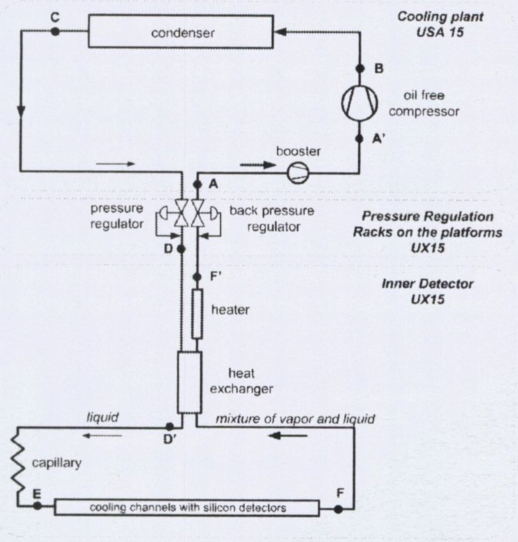


Fig. 1. The scheme of the cooling circuit and location of its sub-sections

Rys. 1. Schemat obiegu chłodniczego wraz z rozmieszczeniem w odpowiednich sekcjach

The residual liquid in the mixture at the exhaust of the cooling channels is evaporated by means of the power provided by the heater. The heater also raises the temperature of the vapor above the dew-point temperature in the environment.

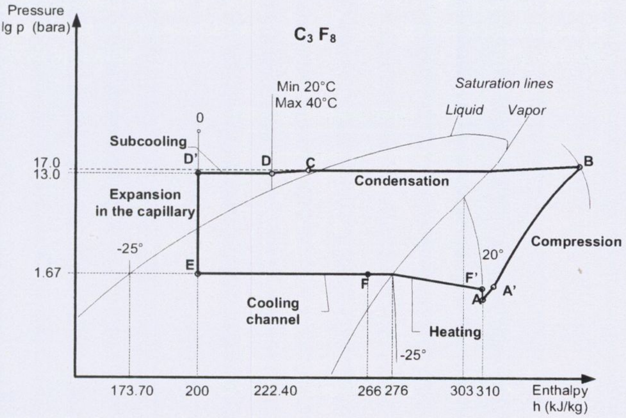


Fig. 2. Coolant circulation of the ATLAS ID evaporative system presented on the C_3F_8 diagram [8]

Rys. 2. Obieg czynnika ziębniczego dwufazowego układu chłodzenia detektorów ATLAS ID na wykresie właściwości czynnika chłodniczego C_3F_8 [8]

3. Octafluoropropane (R218) boiling in small diameter round tubes and non-uniform heating

3.1. Cooling channels for PD and SCT detectors

The cooling channel used in the Pixel Detector cooling system is not a standard one. Special shape of the cooling channel was design according to the silicon layout and readout electronic to increase a contact surface in between detectors and cooling channel (Fig. 3). Round pipe is used in the SCT two phase cooling and silicon detectors are mounted on it by the holder (Fig. 4). Heat from the silicon detectors and readout electronics is provided to the coolant with non-uniform method.

All individual cooling channels in the PD and SCT are mounted around beam-pipe with barrel shape and gravity has an influence to the cooling effectiveness by changing the heat transfer coefficient. There are possible two extreme solution (up/down heat plate position) presented on Fig. 5.

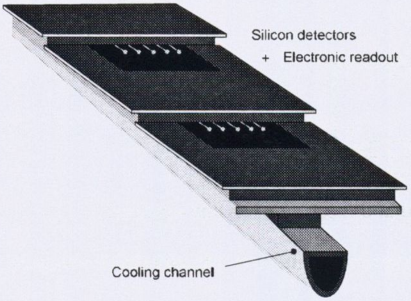


Fig. 3. Cooling channel with silicon detectors and electronic readout used for PD

Rys. 3. Model kanału chłodniczego wraz z zainstalowanymi modułami detekcyjnymi układów PD

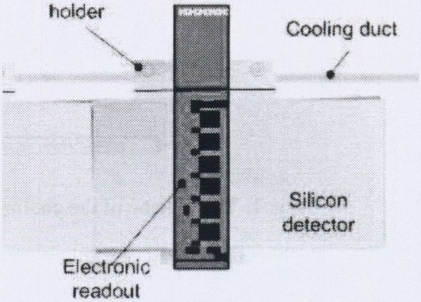


Fig. 4. Cooling channel with silicon detectors and electronic readout used for SCT

Rys. 4. Model kanału chłodniczego wraz z zainstalowanymi modułami detekcyjnymi układów SCT

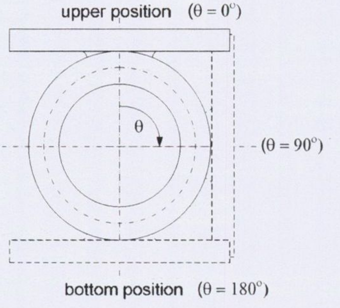


Fig. 5. Extreme position of the heat source in the barrel shape of the PD, SCT detectors

Rys. 5. Skrajne położenie źródła ciepła w ogólnym ułożeniu układu detektorów krzemowych PD, SCT

3.2. Experimental investigation of the heat transfer coefficient

The experimental investigation of the heat transfer coefficient for boiling flow of R218 in small diameter pipe and non-uniform heating were prepared for Pixel Barrel cooling channel model as shown on Fig. 6. The copper round pipe with diameter ID/OD = 4/6 mm have been chosen as cooling channel with soldered heat plate and resistance heater as a heat source. The 5 wall temperatures measurement cross-section were prepared along the cooling channel (Fig. 6 a, b). Experimental model was installed on the testing stand presented on Fig. 7.

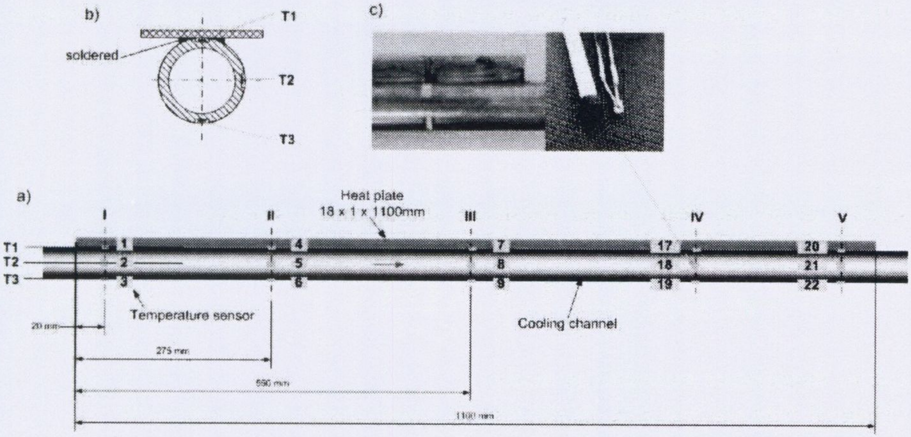


Fig. 6. Cooling channel model of Pixel Barrel silicon detectors

Rys. 6. Model badawczy kanału chłodniczego detektora krzemowego Pixel Barrel

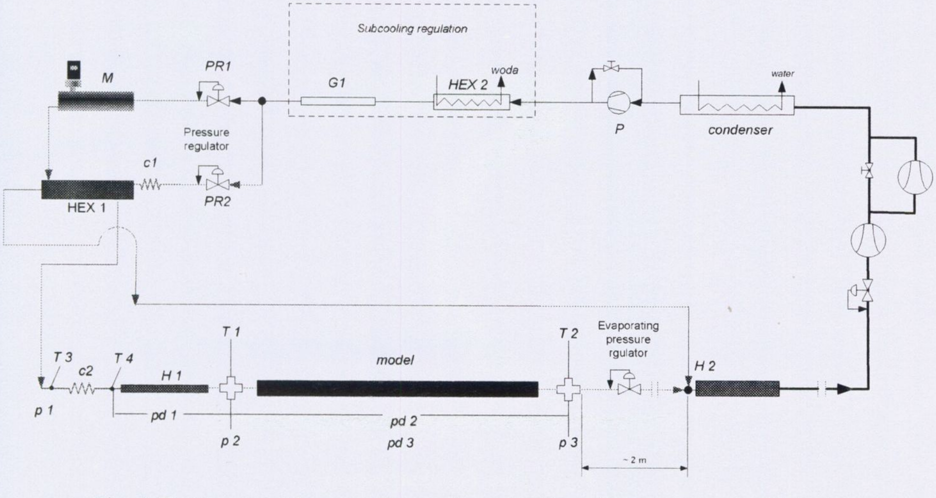


Fig. 7. Testing stand for experimental investigation of heat transfer coefficient

Rys. 7. Stanowisko badawcze wykorzystane do wyznaczenia współczynnika przejmowania ciepła

Measurements were done for evaporating temperature T_s = -14, -12.5, 4, 21.5°C, mass flux $G = 30 \div 520$ kg/(m^2·s), heat flux $q = 1250 \div 25000$ W/m^2, Reynolds number: $1500 \div 16000$, vapour quality – on inlet: 0.1 and outlet: 0.9, different position of the heat source: $\theta = 0, 90, 180^\circ$.

Heat transfer coefficient was determined with Newton equation:

$$\alpha = \frac{\dot{q}}{T_w - T_s} \tag{1}$$

The wall temperature distribution was determined numerically with CFD method in Ansys 6.1® according to the equation (2)

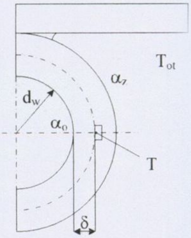
$$-\lambda_r \frac{\partial T}{\partial n} = \frac{T(x,y,z) - T_s}{R(x,y,z)} \tag{2}$$

where:

$R(x,y,z)$ – determine heat transfer resistance and thermal resistance from inside wall surface to mounted temperature sensors:

$$R(x,y,z,) = \frac{d_w + 2\cdot\delta}{\alpha_0 \cdot d_w} + \frac{\delta}{\lambda_r} \cdot \frac{d_w + 2\cdot\delta}{d_w + \delta}$$

$T(x,y,z)$ – temperature measured by sensor.



Thermal field and heat flux distribution was determined with equation (3):

$$\nabla^2 T + \frac{\dot{q}_v}{\rho \cdot c_p} = 0 \tag{3}$$

Fig. 8. Heat flux distribution

Rys. 8. Rozkład gęstości strumienia ciepła

3.3. Overall heat transfer coefficient for boiling flow of R218 in small diameter pipe and non-uniform heating

Based on experimental data and CFD simulation the overall heat transfer coefficient was determined. Theoretical formulas which can be used in presented range of boiling process are method presented by: Chen ([1], [7], [6], [16]) Gungor and Wintertone ([1], [9], [10], [11]), Kandlikar ([1], [4], [7], [13], [15]), Chaddock and Noerager [12], Lazarek and Black [10], [13], [17] or Kew and Cornwell [5]. The worst correlation with experimental data was reached with Chen method (Fig. 9). The Kandlikar method gives the best correlation with experimental data (Fig. 10) in range +70% to -40%. Kandlikar's correlation was chosen to find the new equation constants to reach experimental data with better precision.

Based on [5], [9], Kandlikar's method and experimental data the new correlation was proposed (3.4):

$$\alpha = \alpha_L \cdot \left[C_1 \cdot Co^{C_2} \cdot \left(25 \cdot Fr_L \right)^{C_5} + C_3 \cdot Bo^{C_4} \cdot F_L \right] \cdot \left(1 - x \right)^m \tag{4}$$

were:

α_L – is determine with Dittus-Boelter correlation,
m – exponent = -0,8
C_5 – constant depends on Froude number

$$C_5 = \begin{cases} 0.3 & \text{for } Fr_L < 0.04 \\ 0 & \text{for } Fr_L \geq 0.04 \end{cases} \tag{5}$$

Table 1

Constants C_1, C_2, C_3, C_4 of correlation 4 for R218 boiling flow in small horizontal pipe ID = 4 mm and non-uniform heating

Constant	$Co < 0{,}65$	$Co \geq 0.65$
C_1	0.0194	1.526
C_2	-1.025	3.24
C_3	520.5	413.7
C_4	0.7	

Results of calculated heat transfer coefficient with correlation (4) in comparison to experimental data are presented on Fig. 11. Precision of proposed correlation is ±30% which is on acceptable level.

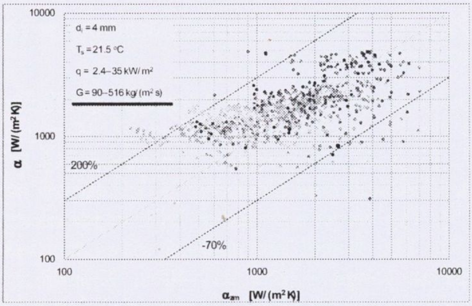


Fig. 9. Comparison of local heat transfer coefficient: experimental and calculated with Chen method [7]

Rys. 9. Porównanie wartości lokalnych współczynnika przejmowania ciepła uzyskanych podczas eksperymentu oraz określonych metodą Chena[7]

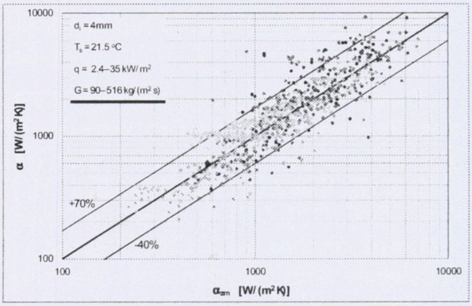


Fig. 10. Comparison of local heat transfer coefficient: experimental and calculated with Kandlikar method [7], $F_L = 2.1$

Rys. 10. Porównanie lokalnych wartości współczynnika przejmowania ciepła uzyskanych podczas eksperymentu oraz określonych metodą Kandlikara [7], $F_L = 2,1$

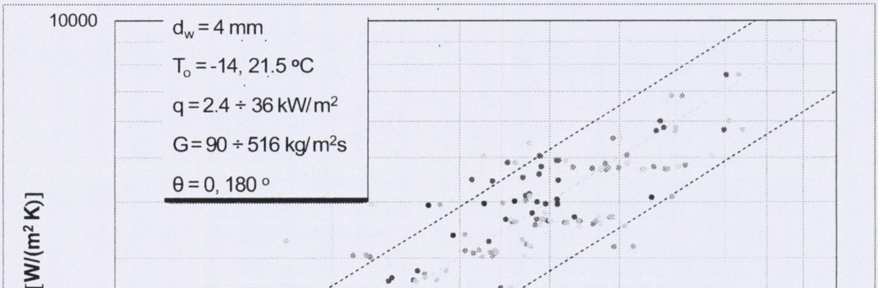


Fig. 11. Local heat transfer coefficient distribution along the cooling channel – experimental and determined with new correlations (4)

Rys. 11. Przebieg zmian lokalnych współczynników przejmowania ciepła określonych za pomocą zaproponowanego wzoru (4) oraz badań eksperymentalnych

4. Concluding remarks

A theoretical methods to determine heat transfer coefficient in the boiling flow in small diameter horizontal pipe and non-uniform heating are not enough precise (3.3). Precision of the determination of heat transfer coefficient value is important when minimum temperature gradient along the cooling channel and minimum mass flow of the coolant is required.

A proposed correlation (4) based on Kandlikar's method can be used instead of standard one equation to determine heat transfer coefficient along the pipe for boiling flow of R218 in the horizontal small diameter pipe and non-uniform heat source.

There is require to find the specific number of the coolant – F_L and all constants of presented equation (4) are based on experimental data. To find the solution for another coolants the experimental investigation must be prepared.

Symbols

Bo – boiling number [-]
Co – convection similarity number [-]
c_p – specific heat [J/(kg K)]
F_L – specific number of the coolant in the Kandlikar's method [-]
Fr – Froude number [-]
G – mass flux [kg/(m^2 s)]
q – heat flux [W/m^2]
Re – Reynold's number [-]
T_s – evaporating temperature [^{o}C]
T_w – wall temperature [^{o}C]
x – vapor quality [kg/kg]
α – heat transfer coefficient [W/(m^2 K)]
α_L – heat transfer coefficient of the coolant liquid [W/(m^2 K)]
α_{zm} – experimental heat transfer coefficient [W/(m^2 K)]
δ – wall thickness [m]
λ_r – thermal conductance of the pipe [W/(m K)]
ρ – coolant density [kg/m^3]
θ – position of the heat plate mounted on the cooling channel model [^{o}]

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