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Surface-Boiling Heat-Transfer in Cylinder-Liner Cooling Space of Diesel Engine

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Abstract :

This paper presents the physical aspects of surface boiling heat-transfer in cylinder-liner cooling space of Diesel engine. Using high-speed Movie-Camera the internal phycical parameters (bubble departure diameter, bubble growth rate and nucleation density) has been studied. A correlation has been developed which can predict the heat transfer coefficient in the cooling space of cylinder-liner of diesel engine.

Notations :

q''—heat flux frominner-tube wall to cooling water
v—water speed in the cooling space
t_w—mean temperature of inner-tube wall
t_f—mean temperature of water in the cooling space
t_{b_1}—temperature of water in the entrance of the cooling space
t_{b_2}—temperature of water in the exit of the cooling space
$\triangle t_s = t_s - t_f$ boiling potential
p—pressure in the cooling space
h—heat-transfer coefficient from inner-tube wall to cooling space
$\triangle p$—variation of pressure in the cooling space
ν—coefficient of kinematical viscosity
a—coefficient of thermal diffusivity
k—coefficient of thermal conductivity
r—tatent heat of evaporation
$L = \frac{\sigma}{\sqrt{\rho' - \rho''}}$ arbitrary size of bubble
σ—surface tension force
ρ'—density of water
ρ''—density af steam
c—specific heat of water
w—speed of steam generation $w = \frac{q''}{r\rho''}$
ni—number of bubbles having the same diameter
ni'—number of bubbles having the same deporting time
N—the total number of bubbles that was taken in to consideration
τ—bubble departure time
f—bubble departure frequency
D—bubble departure diameter
N'—number of bubbles on the cooling surface
q—amount of heat taken away by one bubble
F— area of the cooling surface
C_1, a_1, a_2 are constants.

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Introduction :

Heat-transfer with surface-boiling continues to be one of the most important processes in modern supercharged diesel-engine. Designing end exploitation of modern supercharged diesel engine shows that the temperature of cylinder-cooling surface exceeds the saturation temperature of the coolant at the given definite pressure. The temperature of the thermal boundary layer may also exceed the saturation temperature of the coolant, where as the rest of the cooling liquid in the jacket-space having the mean temperature below saturation An isothermal surface divides the coolant a thin boiling boundary layer and a relatively cold flowing liqud in the cooling space. Firstly on the cooling surface (in the micro-cavity) originates micro-steam bubbles, increases in size and is departed from the micro-cavity. After departing from micro cavities the bubbles are collapsed in relatively cold flowing liquid. Heat transfer in this case is considered as a special form of mass-transfer where as new phase (steam) originates, detaches and intensity the destruction of thermal boundary layer. As a result of this heat-transfer coefficient is extremely increased. The temperature of cylinder surface is decreased. It creates the best circumstances for further chagring of the engine in order to increase the effective power of the plant.

However, in heat engineering the terminology 'Surface-boiling' is known too long ago. From 1936 this process has its great application in cooling highly thermaly loaded appartus like atomic reactor, rocket installation and aviation engine.

Many works have been done by renowned thermal physicist Kytateladge (1) Tolubinsky (2) Rohsenow (3) Snaidar (4) MC Adams (5) Nikiyma (6) Nishikawa (7) Hara (8).

Studies on surface-boiling heat-transfer may be roughly divided into three categories.

(1) A study on hydrological resistance in the cooling system when surface-boiling takes place.

(2) A study on critical heat-flux leading to film-boiling.

(3) A study on the laws of surface-boiling.

The first two categories of work were performed where heat-flux varied from 1000-5000kw/m^2 and coolant-speed was varied from (3-15) m/sec. That is why in production of diesel-engine these works have no special interest.

The process surface-boiling was observed in cooling space of diesel engine by many scintists (9, 10, 11, 12). The process has its advantages over the heat-transfer in forced convection. It decreases the thermal loading of the cylinder-piston group. It equalizes temperature slope of the whole cooling surface and it decreases cavitation errosion of cylinder-liner.

The main thing is that there is no unified model of surface boiling heat-transfer. The existing hypothesis partly explain different aspects of the same process. However, at present model of Snaidar and Robin (4) may be considered more applicable and practical.

Due to complexity of the process there are no closed system of equations which can be proposed to write down the process surface boiling. Above authors have no unity in their opinions about the physical aspects of the problem. The internal physical parameters of 'surface boiling' (departing bubble diameter, frequency of departing bubbles, nucleation density) in the cooling space are not studied yet perfectly.

Experimental set-up and procedure :

A study of internal physical parameters of surface boiling heat-transfer in cooling space of real diesel engine is too difficult. That is why an experimental set up was designed stimulating approximately the same conditions of cooling of cylinder-surface. The set-up is a concentric 'tube within a tube' heat-exchanger. The innertube is of 50 mm diameter and 260 mm in length. The outer-tube acting as a cooling jacket has its diameter of 74 mm, so that the annular gapi s of 12 mm. Projector lamps were placed the surface of the inner-tube. Heat flux q'' was varied from 50 Kw/m^2 to 150 Kw/m^2, water is supplied continuously by a centrifugal pump in the cooling jacket in order to cool surface of the inner-tube. Nine copper-constantous thermocouples here placed on the surface of the inner-tube in order to measure the wall temperature t_w. Two thermocouples in entrance and the other two thermocouples were placed in exit on the cooling jacket to measure the temp of cooling water. The mean temp was calculated using the relation $t_f = \frac{2(b_1+b_2)}{4}$

The heat-exchanger has three glass-windows fixed with its three walls for visual observation and photography of boiling process. The experimental setup and experimental section are shown in fig 1 and 2.

Experiments were performed in series according to the following regime parameter :

water speed, V varied from 0.05 to 0.15 m/sec.
heat flux q", - 30 - 150 kw/m^2
potential of boiling $\triangle t_s$ — 5°C to 40°C

In the first series of experiments, the effect of water-speed to the thermal condition of cylinder surface and intensiffication of heat-transfer in the cooling space were studied at different cooling temperature.

In the second series of experiments, the effect of cooling temperature and heat-flux to the thermal condition of cylinder and intensification of heat-transfer in the cooling space were studied.

High-speed and static photography were taken after having a stable regime in definite combination of regime parameters. In order to determine the size of bubbles a calibration wire (diameter 0.2 mm) was fixed on the surface of the inner tube, Speed of movie-camera was in the range of 300 frame/sec to 5000 frame/sec. For statical photography a 'Zenit EM' camera was used.

Results :

First series of experiments conclude that (as shown in fig. 3) if $t_w < t_s$, water speed plays a vital role in intensification of heat-transfer in the cooling space. And heat-transfer takes place in the regime named forced convection. And if $t_w > t_s$, surface-boiling takes placei n the thermal boundary layer, origination, growth, departure and collapse of bubbles compell the cooling water in a turbulent-flow in the cooling jacket as a result of this heat-transfer coefficient extremely increases. In this case water speed in the cooling space practically does not influence in heat transfer. This phenomenon is paradoxial in accordance with forced convection.

Second series of experiments indicate that (Fig. 4) surface-boiling in the cooling space takes place in definite combination of regime paraemters. It in the definite regime heat-flux is increased surface boiling takes place at a lower cooling temperature of the coolant.

Results obtained from photography shows that the process surface-boiling is a stokhastical phenomenon. In the definite constant regime all the physical parameters (depating bubble diameter D, departing bubble frequency f, and nucleation density of bubble) were varied from point to point on the cooling surface and with the time.

In order to determine the mean value of physical parameters the mathematical statistics was used. Bubble departure diameter and frequency of departing bubbles can be expressed by Gamma-function as shown in fig 5 and 6. Nucleation density can be expressed by poission distribution. The nature of distribution curves remain constant in the experimental regime-parameters.

With the increasing of heat-flux (in a definite mentioned regime) departing bubble diameter (mean statistical value) practically remains constant but the nucleation density is extremely increased. It can be explained that micro-geometry of the cooling surface (more-micro cavities) were super-heated for the origination of bubbles due to the increased heat-flux.

Boiling potential of coolant practically does not influence the fate of the departing bubble diameter.

Thus the performed research work allow us to explain the internal physical parameters of surface boiling heat transfer in the cooling space of diesel engine.

Correlation of the experimental data :

Data processing was performed in criterial form.

$$Nu_f = \phi \left(Eu_f \cdot Re_f \; Pr_f \; Pe_f K_f\right)$$

Where $Eu_f = \frac{\triangle P}{\rho' V^2}$, $Re_f = \frac{VL}{\nu}$

$$pr_f = \frac{\nu}{a}, \quad pe_f = \frac{WL}{a} \quad K_f = \frac{r}{c.\triangle t_5},$$

$$Nu_f = \frac{hL}{K}$$

Law of conservation of energy can be written as follows

$$q'' = q N' f/F = h(t_w - t_s)$$

As because there was no pressure variation in the cooling space, water-speed has no noticable influence on heat transfer and the ratio ν/a int he experimental regime parameters does not change significantly, so the criteri Eu_f, Re_f and Pr_f were were not taken in to consideration.

$$Nu_f = C_1 \, pe_f^{a_1} \, K_f^{a_2}$$

Using least square method, the coefficients c_1 a_1 and a_2 were determined

$$Nu_f = 479{,}10^{-3} \, pe_f^{0.7} \, K_f^{0.34}$$

The results obtained from models experiments are identical with the experimental results in real diesel engine which concludes that the criterial function can be used in the similar purposes (13)

Comparative study of this criterial function with that of Chirkov (9) Stefanobsky (9) Petrichenko (10) Novennikob (11) shows that the obtained formula is more simple and sufficient reliable for giving the boundary condition in the cooling space of high-speed diesel-engine.

Conclusions :

The main eftective way to decrease the thermal load of cylinder piston group of diesel engine is to intensity the cooling process, the use of surface boiling regime allows to increase the heat-transfer to coolant several times without increasing the power of water-circulation pump.

The proposed criterial function can be used for giving the boundary condition in cylinder cooling space of high speed diesel engine.

The most suggested temperature of the coolant is to be that at which surface boiling takes place in the cooling space of diesel engine.

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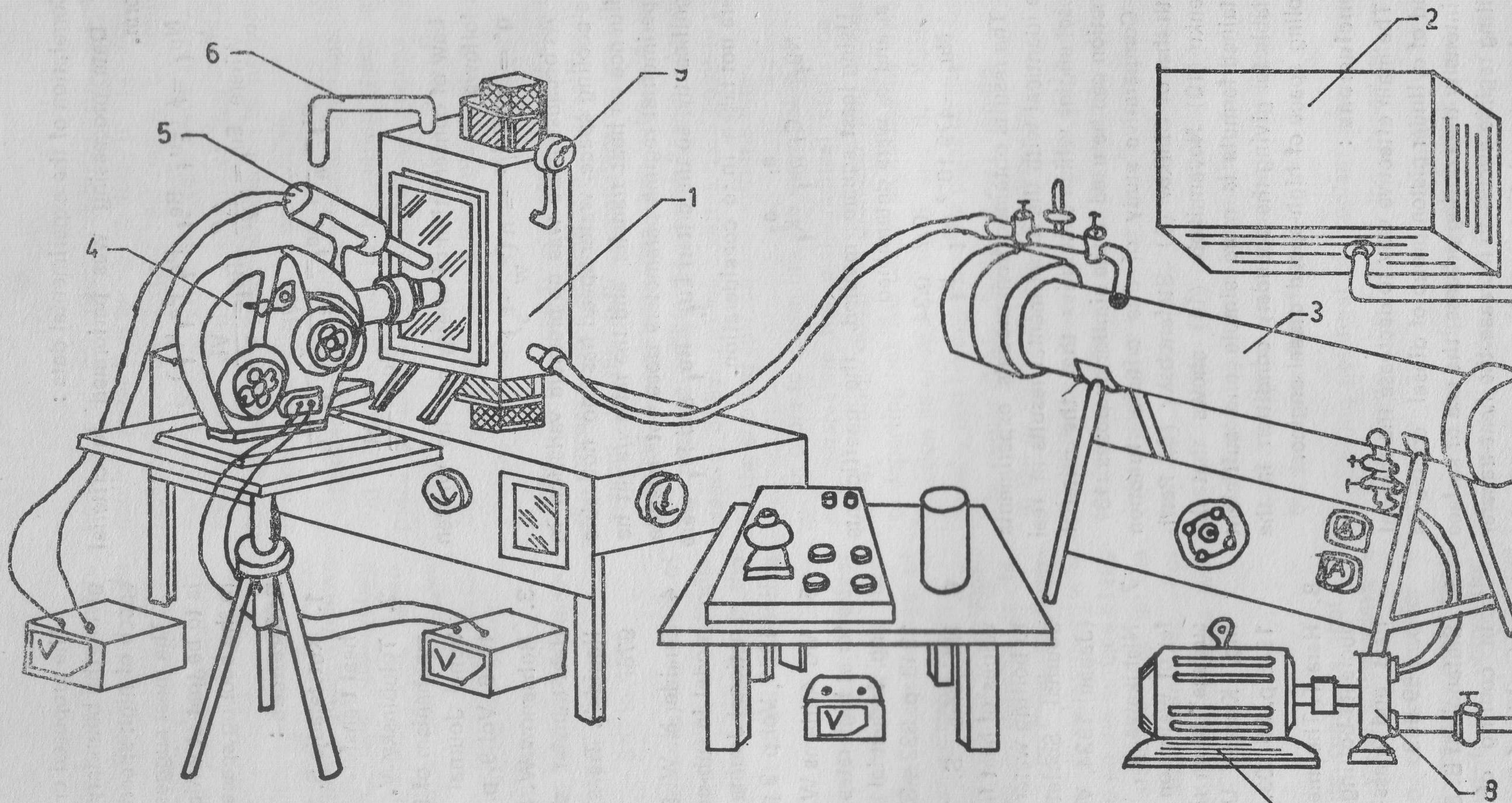
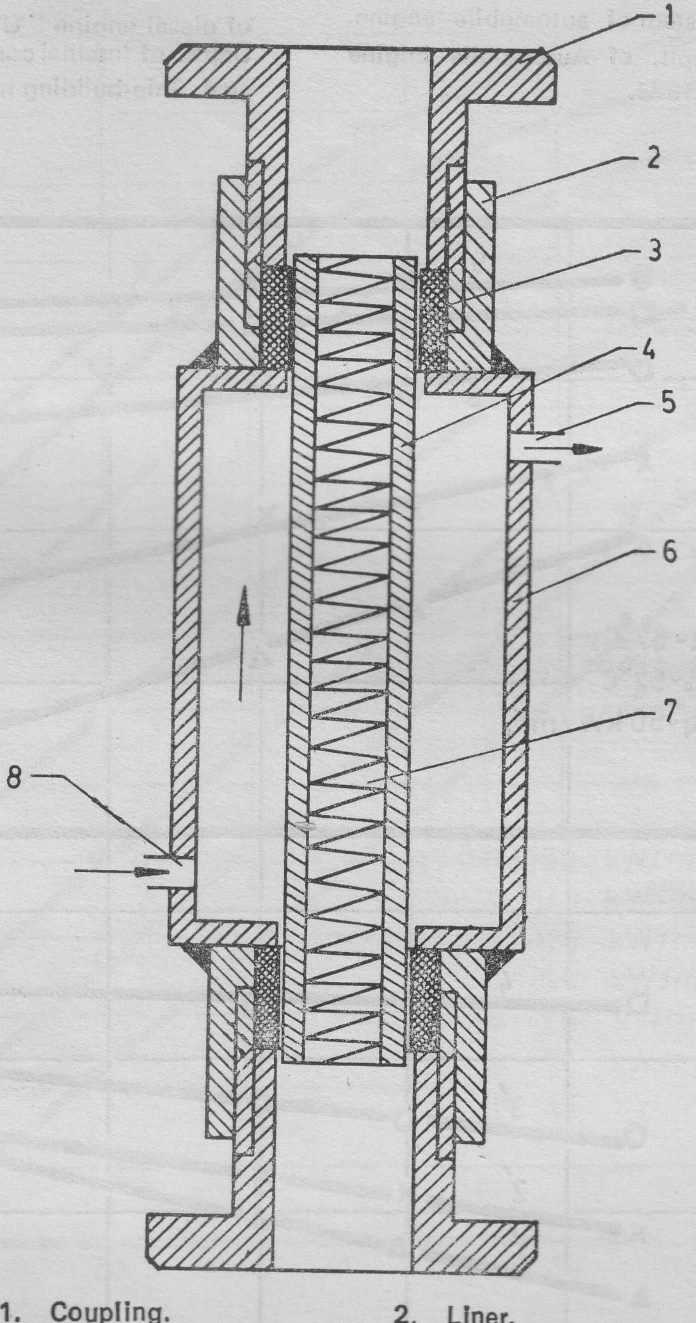


1. EXPERIMENTAL SECTION.
2. STORAGE TANK OF COOLING WATER.
3. ELECTRICAL HEATER.
4. MOVIE-CAMERA-CKC-1M.
5. LAMP FOR ILLUMINATION.
6. EXIT OF COOLING WATER.
7. ELECTRICK MOTOR.
8. WATER CIRCULATING PUMP.
9. MANOMETER.

FIG. 1 EXPERIMENTAL SET UP

EXPERIMENENTAL SECTION



1. Coupling.	2. Liner.
3. Gasket,	4. Expermental Cylinder.
5. Exit of Water.	6. Jacket of Cooling Space.
7. Electric Heater.	8. Entrance of Cooling Water.

Fig. 2. Experimental Section

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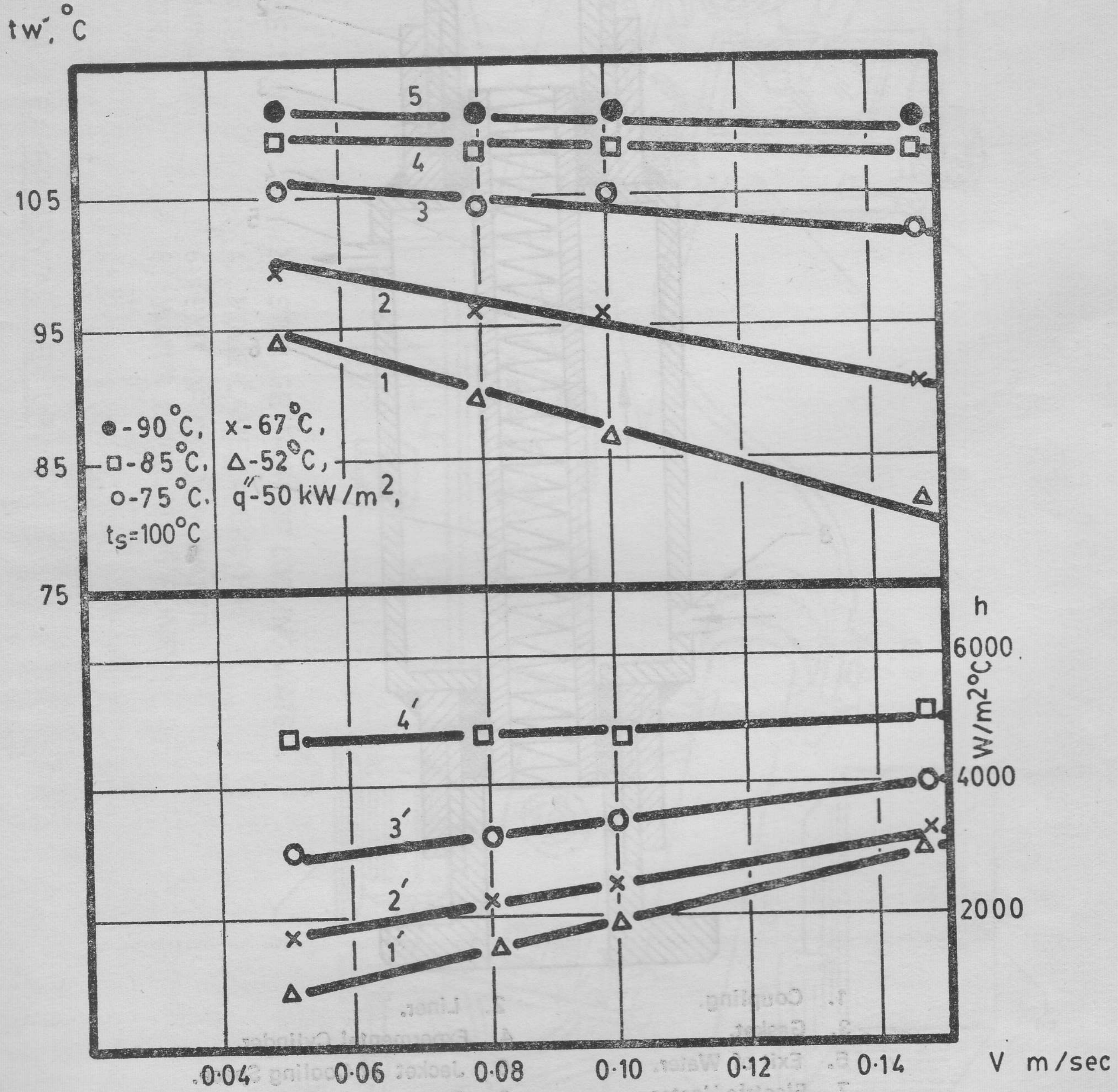
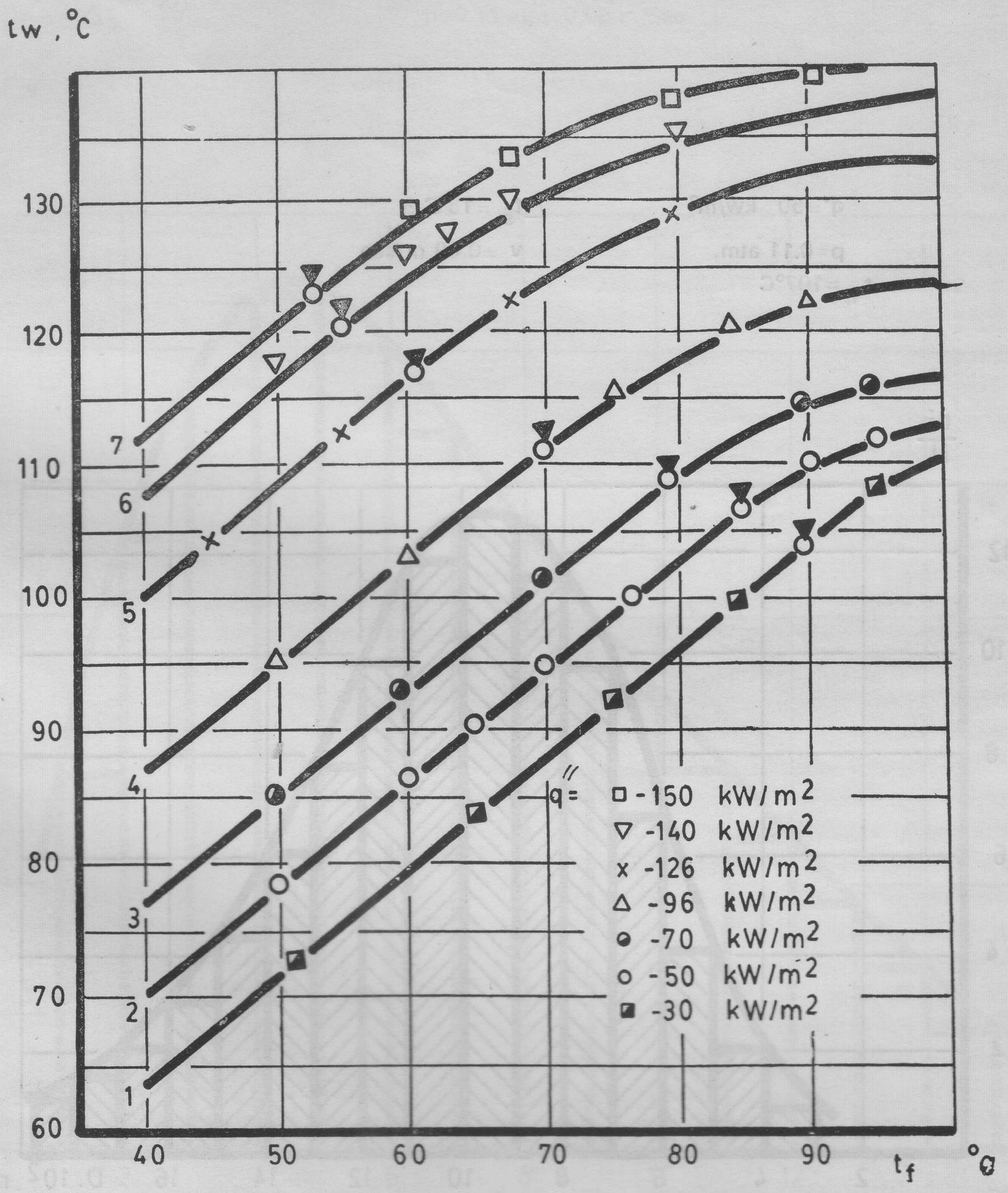


Fig. 3. Effect of Coolant-Speed on the Thermal Condition of Cylinder Surface in the Cooling Space at Different Coolant Temperature



P=0.1 atm, ts=100°C
V=0.09 m/sec

Fig 4. Effect of Cooling Temperature on the Thermal Condition of Cylinder Surface at Different Heat-Flux.

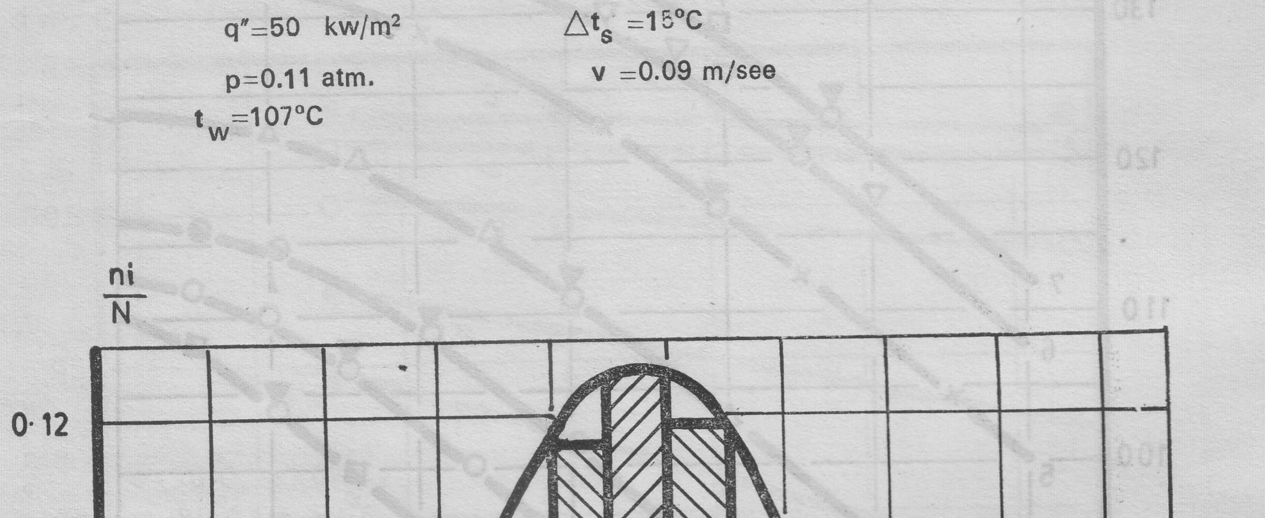


Fig. 5 Distribution of Departng Bubble-Diameter.

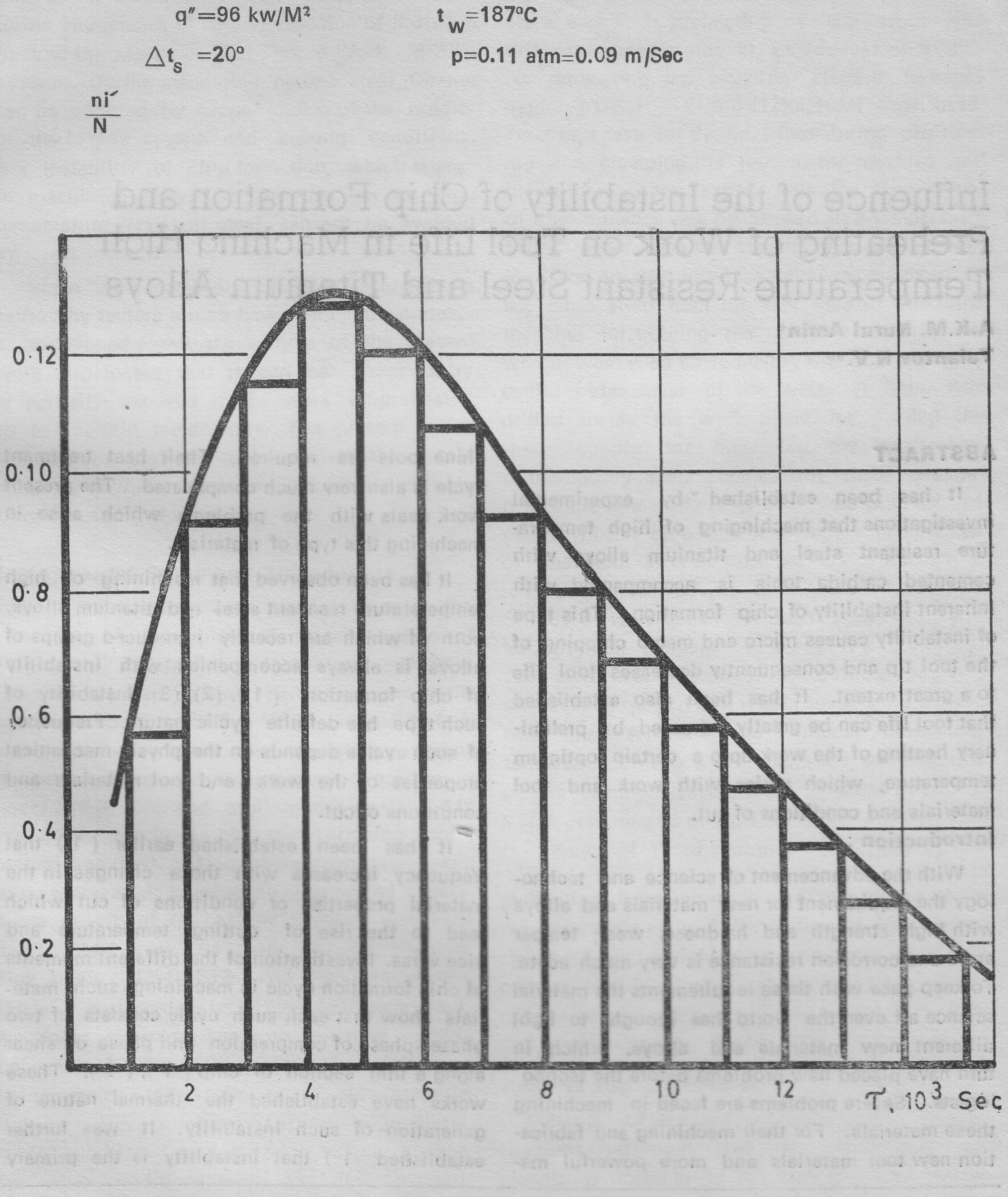


Fig. 6. Frequency Distribution of Departing Bubbles