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A New and Simple Method of Estimating the Liquid Superheat Due to Surface  
Conditions in Nucleate Boiling and its Application to Sodium

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## A New and Simple Method of Estimating the Liquid Superheat Due to Surface Conditions in Nucleate Boiling and its Application to Sodium\*

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*Abstract.* The phenomenon of the bubble growth at the surface of a heating wall due to boiling of the cooling liquid is studied. A new and simple method of calculating the superheat temperature of the liquid necessary to initiate boiling as a function of the surface finish is suggested. A numerical application for sodium is performed.

### 1. Introduction

Liquid metals are extremely good heat transfer media. They are therefore used to cool reactors when the power density is very high. In particular with fast reactors sodium is very often the primary coolant. It is therefore of interest to examine the problem of liquid superheat necessary to initiate boiling, which is particularly serious with sodium, and therefore of the greatest importance, from the point of view of safety, in fast reactors.

It has been shown in recent experimental research [1], [2], [3] that the boiling of a liquid in forced convection in contact with an heating surface does not occur when the temperature of the surface, and therefore the temperature of the liquid in the immediate vicinity of it, has reached the boiling temperature, but a certain excess of temperature is required. A portion of liquid, at least in the immediate vicinity of the heating wall, is therefore superheated. The amount of superheat necessary to initiate boiling depends on the liquid used and on the surface smoothness.

This phenomenon is explained by the following hypothesis: The boiling is promoted by very small bubbles of gas or vapor which are contained in microcavities always present on surfaces. Only when the pressure of the vapor in these cavities is enough higher than the liquid pressure to allow the growth of the bubbles against the contribution of the surface tension of the liquid, can the boiling really start. The wall temperature, at which these bubbles are, must be consequently higher than the saturation temperature of the liquid.

The problem of the superheat is generally not very relevant with water. This is because

1. of the small excess of temperature required for boiling (about 20° C at atmospheric pressure and standard smooth stainless steel surface),

2. only a small portion of the water near the wall is superheated due to the very steep fluid temperature profile in any section, which is characteristic of water and any other fluid with high Prandtl number ( $\geq 0.7$ ),

3. at the starting of the boiling the small amount of steam produced is generally very quickly reconverted in water by the bulk of the water which is remained in subcooled conditions due to the relatively low ratio of latent heat of vaporization to specific heat of the liquid (540° C at 100° C and atmospheric pressure, against an average value of 3300° C for sodium).

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This is not generally the case with liquid metals and, in particular, with sodium. We will see in the later paragraphs that for the same surfaces the superheat temperature requested to initiate boiling is much higher with sodium than with water. Furthermore, due to the very low Prandtl number of liquid metals (0.01 ÷ 0.005 for sodium) the temperature profile in any section of the liquid is very flat, so, not only a small portion of liquid near the wall is superheated but the whole bulk of the liquid. In addition, the very high ratio of latent heat of vaporization to specific heat of the liquid makes negligible the quantity of energy absorbed by some eventual portion of the liquid which would be in subcooled conditions. If, for any reason or another, the heat flux from the surface increases, or the sodium flow decreases, the beneficial effect of gradual nucleate boiling, generally present with water, does not occur with sodium. Two things are possible: If the surface is sufficiently smooth the wall temperature increases up to melting point without any sodium boiling occurring, or, if the surface is rather rough and high temperature resistant, the wall temperature increases gradually until the great amount of energy stored by the superheated bulk of the liquid is released suddenly producing the instantaneous evaporation of a considerable portion of sodium present with consequent explosion.

In the present paper the phenomenon of the bubble growth at the surface is studied, a new and simple method of calculating the superheat temperature necessary to initiate boiling as a function of the surface finish is suggested and a numerical application for sodium is performed.

### 2. The physical problem

Consider a microscopic cavity in the heating wall (see Fig. 1) which contains a certain amount of vapor. For simplicity we assume that the opening of the cavity is circular and of radius  $r_0$ . The angle  $\Theta$  that the separation surface between liquid and vapor makes with the heating wall at the moment of detachment of the bubble from the wall varies with the liquid and the material from which the wall is made. For liquids which wet the wall, such as water, sodium, and other liquid metals with the exception of mercury,  $\Theta$  is always less than 90°. Liquids which do not wet the wall are very poor heat transfer media and therefore not interesting as practical coolants. If  $p_l$  and  $p_v$  are respectively the liquid and the vapor pressure and  $\sigma$  the liquid surface tension, the equilibrium of the forces on the separation surface between vapor and liquid is given by the equation:

$$p_v - p_l = \frac{2\sigma}{r} \quad (1)$$

(see Appendix I)

where  $r$  is the curvature radius of the separation surface between liquid and vapor. If  $\beta$  is the angle that the bubble surface makes with the wall surface, one can write:

$$r = \frac{r_0}{\sin(180-\beta)} = \frac{r_0}{\sin\beta} \quad (2)$$

Therefore

$$p_v - p_l = \frac{2\sigma}{r_0} \sin\beta \quad (3)$$

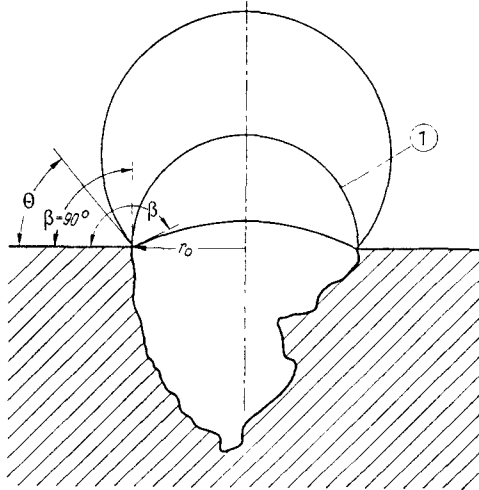


Fig. 1. The growth of the bubble

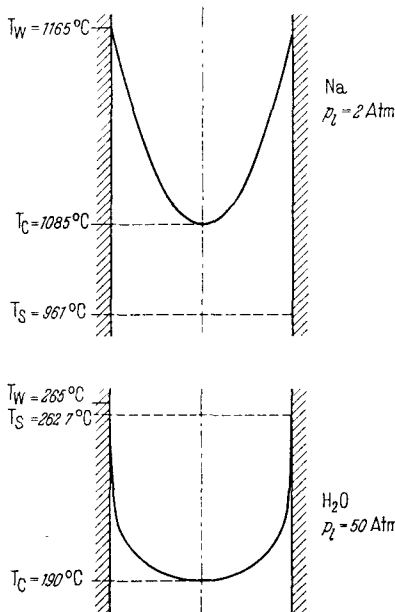


Fig. 2. Typical temperature profiles in sodium and in a water cooled channel

Heat flux = 300 W/cm<sup>2</sup>  
 Channel diameter = 0,8 cm  
 Liquid velocity = 800 cm/sec

From Fig. 1 is quite clear that  $\beta$  can have any value between  $180^\circ$  and  $\Theta$ , and because  $\Theta \leq 90^\circ$  the maximum value of  $\sin\beta$  is for  $\beta = 90^\circ$ , then:

$$(p_v - p_l)_{\max} = \frac{2\sigma}{r_0} \quad (4)$$

It is important to notice that if the liquid does not wet the wall,  $\Theta > 90^\circ$ , and

$$(p_v - p_l)_{\max} = \frac{2\sigma}{r_0} \sin\Theta \quad (5)$$

Eq. (4) was already obtained, using a different reasoning, by GRIFFITH and WALLIS [1] and it explains physically the reason of the superheat. Only when the pressure of the vapor in the cavity has reached the value  $p_v$  equal to  $p_l + \frac{2\sigma}{r_0}$  the bubble can grow up to the position (1) of Fig. 1. After that point the pressure  $p_v$  is in excess of  $p_l + \frac{2\sigma}{r}$  because  $r > r_0$ , and the bubble increases until detachment, when  $\beta$  has reached the value  $\Theta$ . Subsequently the vapor remained in the cavity produces a new bubble and the above process is repeated all over again. The vapor in the cavity is obviously saturated, so the temperature  $T_{1r}$  of the wall, which is the same as that of the vapor in the cavity and corresponds to the pressure  $p_v$ , is higher than the saturation temperature  $T_S$  which corresponds to the pressure of the liquid  $p_l$ . The liquid in the immediate vicinity of the wall is at the temperature  $T_{1r}$  and it is therefore superheated by the amount  $T_{1r} - T_S$ . The maximum portion of the liquid which can be in superheated conditions depends on the ratio  $(T_w - T_S)/(T_w - T_C)$  where  $T_C$  is the temperature in the center of the cooling channel. A typical situation for water and sodium is shown in Fig. 2. One can see that while a small portion of water can be in the worst conditions, superheated, the whole sodium present can be superheated to a large amount. The comparison is been made for the same surface finish (the same  $r_0$ ) and the same heat flux. Fig. 2 shows also that subcooled boiling is possible with water, but practically impossible with sodium.

### 3. Previous literature

GRIFFITH and WALLIS [1] and HOFFMAN and KRAKOVIAK [3] did not use Eq. (4) for their calculation of the liquid superheat, but, by means of simplifying assumptions, transformed it into another more apt form for numerical evaluation. It is worthwhile here to report briefly their method. The Clausius-Clapeyron relation [4] is:

$$\frac{dp}{dT} = \frac{h_{lv}}{(v_v - v_l)T} \quad (6)$$

where  $p$  and  $p + dp$  are the saturation pressures corresponding respectively to the evaporation temperatures  $T$  and  $T + dT$ ,  $h_{lv}$  is the latent heat of evaporation at the temperature  $T$ , and  $v_v$  and  $v_l$  are the specific volumes of saturated vapor and liquid at the temperature  $T$ .

GRIFFITH and WALLIS assumed that Eq. (6) is valid also in finite difference form between the two temperatures  $T_S$  and  $T_{1r}$ . This is a good approximation for small differences between  $T_{1r}$  and  $T_S$ , but it is certainly not a good one for liquid metals where  $T_{1r} - T_S$  can be of the order of hundreds of degrees centigrade. How will be shown later. Indeed, one has uncertainty in knowing at which temperature to evaluate the second term of Eq. (6). GRIFFITH and WALLIS opted for temperature  $T_{1r}$  and wrote:

$$\frac{p_v - p_l}{T_{1r} - T_S} = \left( \frac{h_{lv}}{v_v - v_l} \right)_{T_{1r}} \frac{1}{T_{1r}} \quad (7)$$

From Eqs. (4) and (7) one obtains:

$$T_{1r} - T_S = \frac{2\sigma}{r_0} \left( \frac{v_v - v_l}{h_{lv}} \right)_{T_{1r}} T_{1r} \quad (8)$$

HOFFMAN and KRAKOWIAK [2] opted to evaluate the second term of Eq. (6) at the temperature  $T_S$ . With two other simplifying assumptions: that  $v_l$  is negligible in comparison of  $v_v$ , and that the saturated vapor in the bubble behaves like a perfect gas, they obtained:

$$T_W - T_S = \frac{2\sigma}{r_0} \left( \frac{v_v}{h_{lv}} \right)_{T_S} \quad T_S = \frac{2\sigma}{r_0} \frac{R T_S^2}{h_{lv} p_l} \quad (9)$$

where  $R$  is the gas constant of the vapor considered as a perfect gas. Of course neither Eq. (8) nor Eq. (9) is really exact. We feel that an evaluation of the second term of Eq. (6) at an average temperature between  $T_W$  and  $T_S$  would have been a better approximation than the both previous.

4. The new method

In reality once one has Eq. (4), it is not necessary to use the Clausius-Clapeyron relation to evaluate the liquid superheat  $T_W - T_S$ . It is possible to obtain  $T_W - T_S$  as a function of  $T_S$  and  $r_0$  directly from Eq. (4). To explain this method more clearly we will present it with an example in the case of sodium, but this method is perfectly general and valid for any liquid.

Fig. 3 shows the vapor pressure of sodium versus temperature. All the sodium physical properties are from [5]. In the diagram the ratio  $2\sigma/r_0$  is also plotted for various values of  $r_0$ . Starting from a certain temperature  $T_W$  in abscissa one can read in ordinate the value of  $p_v$  from the vapor pressure curve\* and the ratio  $2\sigma/r_0$  for a certain value of  $r_0$ , where, quite clearly,  $\sigma$  must be evaluated at  $T_W$  because this is the temperature of the liquid at the surface of the bubble.

The difference  $p_v - \frac{2\sigma}{r_0}$  which can be read directly on the diagram gives the pressure  $p_l$  [see Eq. (4)]. From the value of  $p_l$  in ordinate one can read from the vapor pressure curve the value of  $T_S$  and then obtain the corresponding value  $T_W - T_S$ . The results of this procedure are reported in Fig. 4. One can see that the amount of superheat is fairly high especially for low values of  $r_0$ . Practical values of  $r_0$  can be obtained from the experiments with potassium of HOFFMAN and KRAKOWIAK [2]. Their experimental results are reported in Fig. 5, which shows also the theoretical curves according their and our methods. Our curves were obtained using values of  $\sigma$  for potassium from [6], [7], [8] and temperature vapor pressure relationship given by [9].

The difference in estimating the value of  $T_W - T_S$  according to the two different methods is not very great in the range  $400 \leq T_S \leq 750^\circ \text{C}$ . This is especially true considering the uncertainty in the value of  $\sigma$  for potassium. However, for higher  $T_S$  the difference becomes considerable. By evaluating the Hoffman and Krakowiak experimental points with the present, more exact, theory one finds that for a normal smooth stainless steel surface  $r_0$  is  $0.25 \mu$ , while for a porous surface the group of minimum  $r_0$ 's lies in the region of  $r_0 = 0.75 \mu$  and the majority of pores is in the range  $10 \div 50 \mu$ .

\* In this, one must assume that the cavity is filled with sodium vapor and not another vapor or gas. This is quite acceptable because, due to the very good wetting qualities of sodium, after a while practically all the surface cavities will be filled by sodium, liquid or vapor, and in any case the greater part of vapor which goes to increasing the volume of the bubble cannot come other than from the nearby sodium.

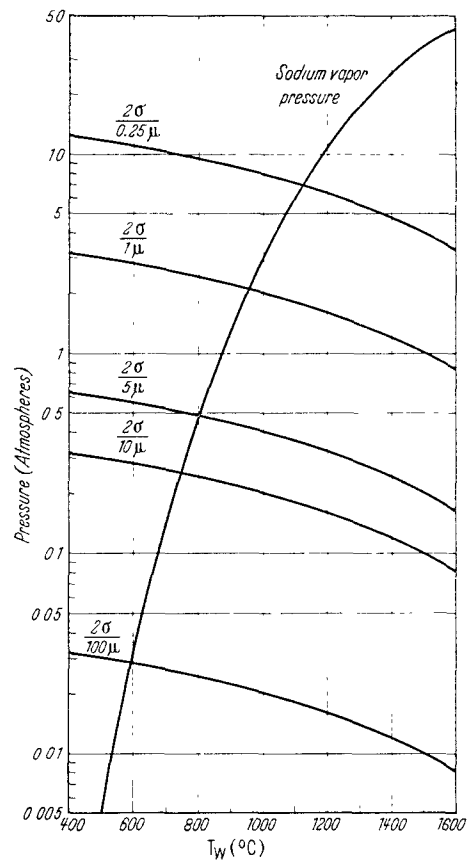


Fig. 3. Sodium vapor pressure and  $2\sigma/r_0$  ratio versus wall temperature

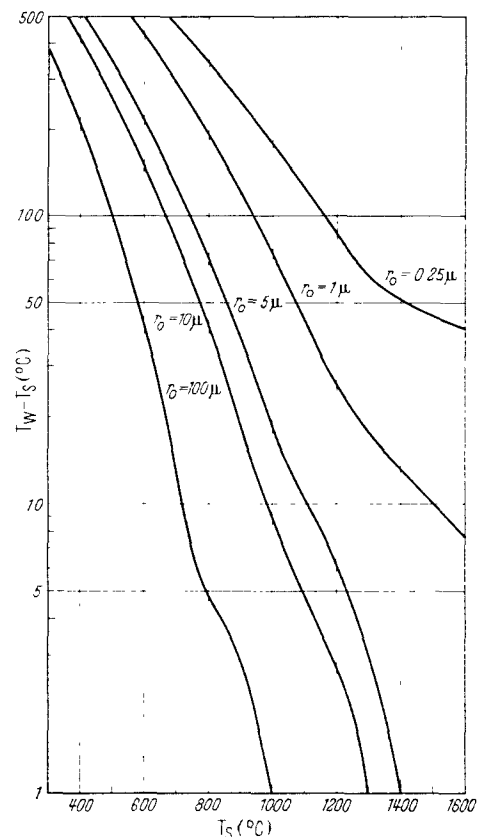


Fig. 4. Sodium liquid superheat as function of saturated temperature and surface finish ( $r_0$ )

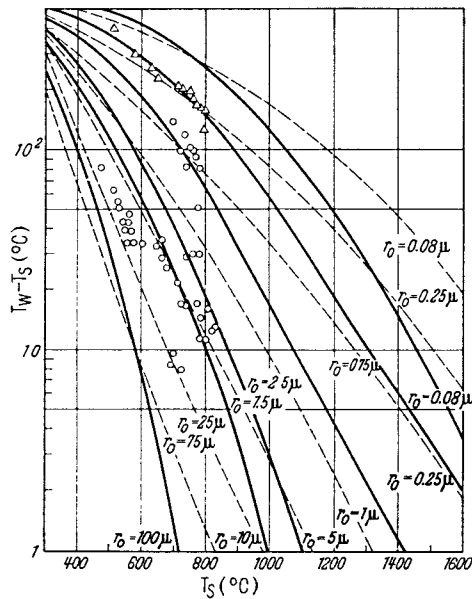


Fig. 5. Potassium liquid superheat as function of saturated temperature and surface finish ( $r_0$ ). ----- according to HOFFMAN and KRAKOVIK; — according to present calculation. Experimental points [9]:  $\Delta$  smooth surface,  $\circ$  rough surface

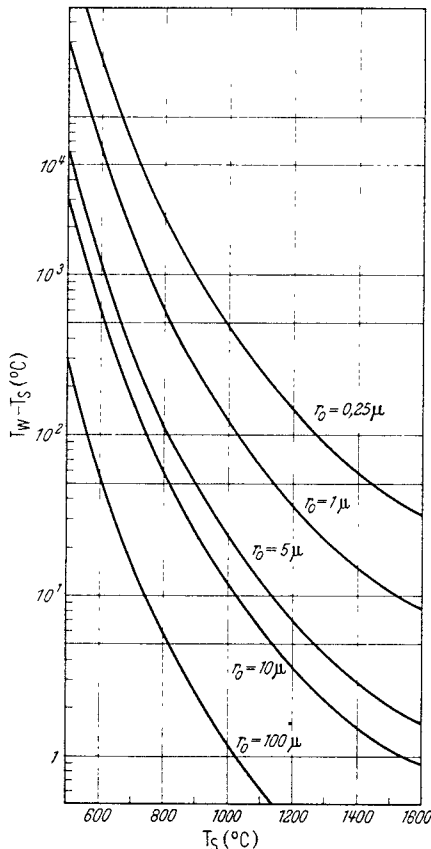


Fig. 6. Sodium liquid superheat as function of saturated temperature and surface finish ( $r_0$ ), according to HOFFMAN and KRAKOVIK

For sodium the difference between our and HOFFMAN and KRAKOVIK'S approach is very relevant. Fig. 6 shows the curves  $T_W - T_S$  versus  $T_S$  obtained with the Hoffman-Krakoviak method [Eq. (9)]. One can see that the introduction of their simplifications makes a great difference; i.e. at  $T_S = 960^\circ\text{C}$  and  $r_0 = 0.25 \mu$  Eq. (9) gives  $T_W - T_S = 620^\circ\text{C}$  instead of  $204^\circ\text{C}$  obtained with the present method.

The reason why the Hoffman-Krakoviak approximation applies better with potassium than with sodium is that the superheat  $T_W - T_S$  with sodium is considerably higher than that with potassium, thus the approximation of replacing an equation in differential form [Eq. (6)] with another in finite difference form [Eq. (9)] is obviously less exact.

##### 5. The consequences in a sodium cooled core

In a sodium cooled reactor the sodium pressure at the core outlet could be as low as 2 Atms. This pressure corresponds to  $T_S = 961^\circ\text{C}$ . If the fuel elements have smooth stainless steel surfaces,  $r_0 = 0.25 \mu$  and the maximum possible  $T_W - T_S$  is  $204^\circ\text{C}$  (see Fig. 4). If now for any reason, for instance fuel rods bending due to thermal stresses, the cross section area of the cooling channel decreases, the coolant velocity decreases and the fuel element surface temperature can increase up to  $1165^\circ\text{C}$  without any boiling occurring. Consider for instance the extreme case that the sodium velocity is reduced to zero. The surface temperature and the temperature of the whole sodium present in the cooling channel cross section, increases until  $1165^\circ\text{C}$  at which time the fraction  $204^\circ\text{C}/3300^\circ\text{C} = 6.2\%$  of the sodium present vaporizes,  $3300^\circ\text{C}$  being the average ratio of latent heat of vaporization to specific heat of sodium. In the other extreme, but less practical case, in which the sodium maintains the nominal velocity and the sodium boiling is produced by excessive heat flux, the vaporizing fraction is slightly lower. Consider for instance the case, typical of a fast sodium cooled reactor, of a sodium mean velocity of 8 m/sec, a channel hydraulic diameter of 0.8 cm and a nominal heat flux of  $300 \text{ W/cm}^2$ . When the temperature  $T_C$  of the sodium, due to excessive heat flux in the upstream portion of the channel, reaches  $1085^\circ\text{C}$ ,  $T_W$  is  $1165^\circ\text{C}$  and the boiling occurs. The average difference between the sodium temperature and  $T_S = 961^\circ\text{C}$  is  $164^\circ\text{C}$ , where the sodium temperature profile is considered, with good approximation, to be a parabola of second degree. The sodium vaporizing fraction is therefore  $164^\circ\text{C}/3300^\circ\text{C} = 4.9\%$ . In practice the real case will lie between these two extremes.

These percentages, although in absolute not very high, are already sufficient to give to this vaporization the character of a real explosion. That is the production of 4.9% and 6.2% vapor at  $961^\circ\text{C}$  means an increase in volume 65 and 80 times, respectively, with respect to the initial liquid only volume.

The problem of sodium superheat is particularly serious because sodium, and other alkali metals, wet surfaces so well that only very small cavities are not filled by liquid. The use of a rough surface does not reduce the danger of a liquid superheat very much. For instance if one uses a rough surface similar to that used by HOFFMAN and KRAKOVIK, cavities with  $r_0 = 0.75 \mu$  are still active. This corresponds to a superheat of  $120^\circ\text{C}$  for sodium at 2 Atm and to an increase in volume of 47 times for the case of boiling occurring due to stoppage of sodium flow. Thus the improvement due to the use of a rough surface is only that of reducing the maximum possible wall temperature from  $1165^\circ\text{C}$  to  $1081^\circ\text{C}$  and the increase in volume due to vaporization from 80 times to 47 times.

### 6. Conclusion

The amount of liquid superheat required to initiate boiling in sodium is very high. With the method presented in this paper it is possible to calculate this superheat as a function of liquid pressure and heating surface finish. The previous approximated formula suggested by HOFFMAN and KRAKOVIAK gives superheat temperatures which are in certain cases, as much as three times in excess.

For sodium at 2 Atm and a smooth surface, the liquid superheat is 204° C and the wall surface temperature would reach 1165° C before the nucleate boiling would start. At this temperature the great amount of energy stored in the superheated sodium is released suddenly producing the instantaneous evaporation of about 5% of the sodium present with consequent explosion. This happens unless the fuel element does'nt melt before reaching that temperature.

The problem of sodium superheat is particularly serious, because sodium wets surfaces so well that only very small cavities are not filled by liquid sodium. The use of a rough surface does'nt significantly reduce the danger of a liquid superheat. According to our calculation the presence of a rough surface would only reduce the increase in volume due to vaporization from 80 times to 47 times with sodium at 2 Atm.

### Acknowledgement

The author wishes to thank Mr. D. ARZT who made the numerical calculations and the drawings.

### Appendix I

#### Calculations of the static equilibrium equation of a bubble

Consider an imaginary section across a spherical bubble of radius  $r$  (see Fig. 7). Each of the two sections of the sphere must be in static equilibrium. Consider for instance the section the center angle  $\alpha_0$  of which is  $< 90^\circ$ . This is subjected to the pressure  $p_v - p_l$ , which for symmetry results in a force directed along the axis of the section and given by:

$$\int_0^{\alpha_0} (p_v - p_l) 2\pi r \sin \alpha r d\alpha \cos \alpha = (p_v - p_l) \pi r^2 \sin^2 \alpha_0.$$

This force is balanced by the surface tension  $\sigma$  which for symmetry is constant along the border of the section and tangent to the sphere. Thus the resultant of the  $\sigma$  forces is also directed along the axis of the

section and is given by:

$$2\pi r \sin \alpha_0 \sigma \cos (90 - \alpha_0) = 2\pi r \sigma \sin^2 \alpha_0$$

and the equilibrium is given by

$$(p_v - p_l) \pi r^2 \sin^2 \alpha_0 = 2\pi r \sigma \sin^2 \alpha_0.$$

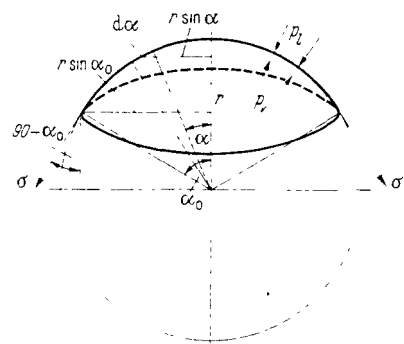


Fig. 7. Equilibrium of the forces for a spherical bubble

Therefore

$$p_v - p_l = \frac{2\sigma}{r}.$$

The reasoning is perfectly analogous for  $\alpha_0 > 90^\circ$  and gives the same results.

**References.** [1] GRIFFITH, P., and J. P. WALLS: Chem. Eng., Symposium Ser. 56, 49—63 (1960). — [2] BERENSON, P.: Transition boiling heat transfer from an horizontal surface. Massachusetts Institute of Technology Report No. 17, Heat Transfer Laboratory, Cambridge, Mass., March 1960. — [3] HOFFMAN, H. W., and A. I. KRAKOVIAK: Convective boiling with liquid potassium. Proceedings of the 1964 Heat Transfer and Fluid Mechanics Institute, Stanford, Calif.: Stanford University Press 1964. — [4] FOÀ, E.: Fondamenti di Termodinamica. Bologna: Edizione Zanichelli 1951. — [5] DUNNING, E. L.: The thermodynamic and transport properties of sodium and sodium vapor. ANL 6246, October 1960. — [6] SPILLER, K. H.: Physikalisch-Thermische Eigenschaften von Na, K und NaK Legierungen im Temperaturbereich zwischen Siedepunkt und etwa 1300° C. EUR 357d, 1963. — [7] SPILLER, K. H.: Zur Kenntnis der physikalischen Stoffeigenschaften von Flüssigmetallen zwischen Schmelz- und Siedepunkt. EUR 599d, 1964. — [8] Gmelins Handbuch der anorganischen Chemie K. 8. Aufl., Nachdruck 1953. Weinheim/Bergstr. und Berlin: Verlag Chemie GmbH. — [9] BURDI, G. F.: SNAP Technology Handbook, Vol. I, Liquid metals. NAA-SR-8617 Vol. I, 1964.

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