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HEAT TRANSFER TO BOILING SKIMMILK

by

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METHOD AND APPARATUS

The rate of heat flow q from a heated wire to a boiling liquid is a function of $\Theta = t - T$, the difference in temperature between the heating surface and the bulk liquid. The curves representing the heat flux $\frac{q(\Theta)}{A}$, where A denotes the area of the heating surface, consist of three parts: the region of convection, in which no vapour bubbles are observed, the region of nucleate boiling, in which vapour bubbles are generated on special spots of the surface, and the region of filmboiling, in which a gradually increasing area of the surface is covered with a coherent layer of vapour. In the regions of convection and nucleate boiling the values of Θ are small or moderate, in contradistinction to the region of film-boiling, where Θ amounts to higher values, up to the melting point of the wire [3, 9]. The coefficient of heat transfer $h = \frac{q(\Theta)}{A\,\Theta}$ amounts to considerably high values in the regions of convection and nucleate boiling only.

In principle the method described by McADAMS [4] has been used to determine the heat transfer curves up to the maximum of nucleate boiling for pasteurized skimmilk, for whey, and for dilutions of either with an excess of water at a pressure of 10 cm Hg. For that purpose a gradually increasing D.C. was passed through a horizontal platinum wire, with diameter D, of which a central portion was isolated as a test section by the use of thin platinum potential taps. This section served as the heating surface and at the same time as a resistance thermometer. The heat flux $\frac{q}{A}$ and the temperature difference Θ were directly calculated from measurements of the potential drop E across the test section, having a length L, and of the current I [4, 8], since the specific resistance of platinum is known as a function of temperature [1]. We have:

$$\frac{q}{A}\ (\text{cal sec}^{-1}\text{cm}^{-2}) = 0.07604\ \frac{EI}{LD}\ (\text{volts amperes cm}^{-2}) \qquad (1)$$

and:
$$\Theta = \varphi(T)\cdot\left(\frac{E}{IR_T} - 1\right) - \frac{D}{8k}\cdot\frac{q}{A} \tag{2}$$

Here R_T denotes the resistance of the test section at the boiling temperature T of the liquid in ohms, which was measured by passing a small current through the circuit while the wire was immersed in the boiling liquid. The multiplication factor $\varphi(T)$ is found to be equal to:
$$\varphi(T) = \frac{1 + BT - CT^2}{B - 2CT} \tag{3}$$

In the term $-\frac{D}{8k}\cdot\frac{q}{A}$ in eq. (2) the radial gradient in temperature within the wire is taken into account. This term, in which k denotes the thermal conductivity of platinum (0.17 cal $sec^{-1}cm^{-1}$ $°C^{-1}$), represents only a small value as wires with diameters of 0.02 cm were used. For these physically pure (99.99 %) wires B was taken as 3.9788×10^{-3} and C was taken as 5.88×10^{-7} if T is expressed in degrees centigrade. The test sections had an average length of approximately 5 cm, and the potential taps had relatively small diameters of 0.005 cm. The wires had previously been annealed at red heat (1000 °C) for 15 min.

According to eqs. (1) en (2) the entire determination of a heat flux curve was restricted to measurements of the potential drop across the test section of the wire, of the heating current, and of the dimensions of the test surface. For this purpose the wire had been connected in series with a standard-resistance of manganin. The potential drop across this resistance of high accuracy was directly proportional to the heating current. This tension and that across the test section were recorded on a potentiometer, after reduction to suitable values by application of tapped shunts. The dimensions of the test surface were measured at room temperature.

Fundamentally the boiling vessel was similar to the one previously described [8, 10]. It consisted of a glass cylinder with ground endfaces. A nickel-plated brass cover ring and base were fastened to the cylinder by means of draw bars, and neoprene rings were used for packing. A pertinax cover was provided with four nickel-coated brass bars. The wire was stretched between two bars, and the potential taps were attached to the remaining bars, placed at a suitable distance from the wire. A total reflux condenser was mounted on the cover plate, and the boiling vessel was only half filled with liquid. It was heated from below by a Bunsen flame to the boiling temperature desired. A constant vacuum was maintained by the combined action of a water jet pump and a Cartesian manostat. Uniform boiling was ensured while the experiments were carried out, as heat losses were replenished by a constant heat supply from the flame.

The time of boiling, preceding the determination of corresponding data in all experiments carried out, was taken approximately equal, allowing a comparison of results obtained for different dilutions investigated.

PRECEDING EXPERIMENTS WITH WATER BOILING AT DIFFERENT PRESSURES

With the object of obtaining suitable reference data, the heat flux $\frac{q}{A}$ to boiling distilled water was determined as a function of the difference temperature Θ. The results at atmospheric pressure are shown in fig. 1. The figures at the curve denote the number of nuclei, generating vapour bubbles on the heating surface, whose test area amounted to approximately 0.31 cm^2. This number increased gradually within the region of nucleate boiling, until filmboiling started. The average diameter of the bubbles emanating from the wire amounted to approximately 0.2 cm. Reproducibility of results at atmospheric pressure is shown at the same time, as data with two separate heating wires are included.

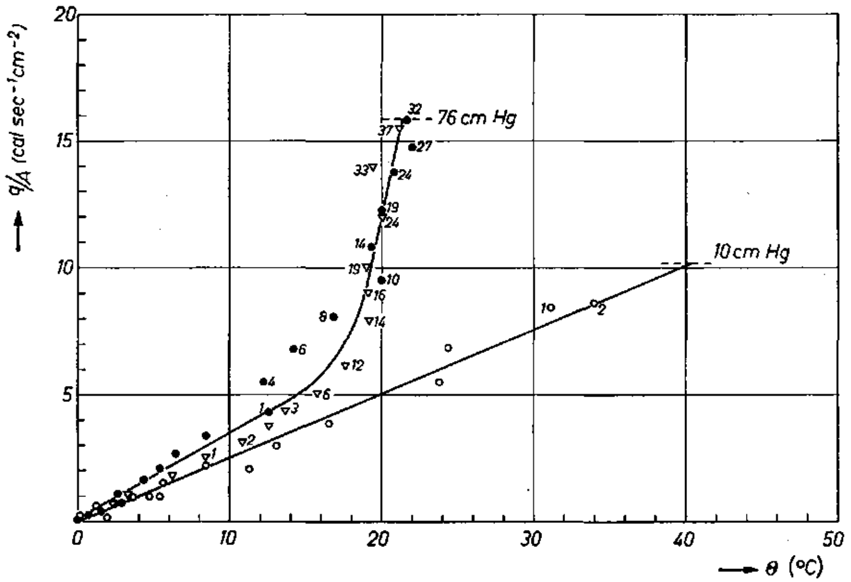

Fig. 1. Heat flux for convection and nucleate boiling in water as a function of temperature difference between heating surface and liquid at atmospheric pressure, and at a pressure of 10 cm Hg.
The figures at the curves denote the number of nuclei generating vapour bubbles.

The heat flux to water at a pressure of 10 cm Hg had also been determined with one of these wires. In this case only two active nuclei generating vapour bubbles, with relatively large diameters of about 1.1 cm, were observed (fig. 1). Apparently the decreasing number of nuclei, active at lower pressure, was setting up smaller circulation currents in the liquid layer surrounding the wire. Consequently the region of nucleate boiling tallied fairly with the linear continuation of the natural convection part of the curve.

The increasing average size of bubbles was obviously responsible for the decreasing maximum of nucleate boiling at lower pressure, as was clearly illustrated by the shape of the curve, showing maximum nucleate boiling to water as a function of pressure p (fig. 2). The maximum increased continuously while the pressure increased and the average size of bubbles gradually decreased. At the same time it was found that the maximum of nucleate boiling approximated a relatively small value of 8 cal $sec^{-1}cm^{-2}$ at pressures below 10 cm Hg. This phenomenon was caused by the fact, that filmboiling started immediately at the appearance on the wire of only one vapour bubble, with a relatively large diameter [11].

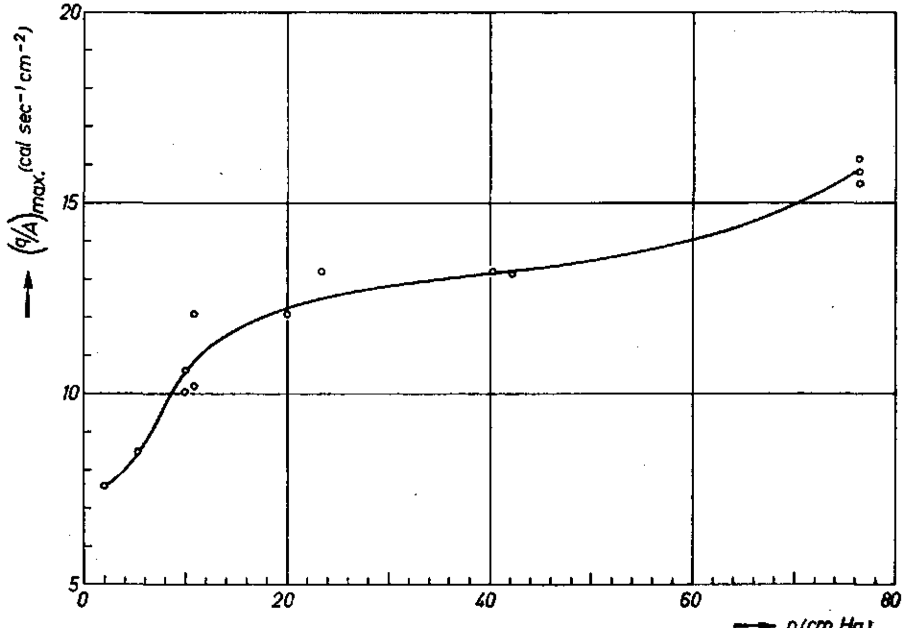

Fig. 2. Maximum of nucleate boiling in water as a function of pressure.

EFFECT OF A CONSTANT NUCLEATE BOILING HEAT FLOW TO SKIMMILK BOILING AT ATMOSPHERIC PRESSURE

A constant heat flow q of 3.45 cal sec^{-1} was supplied to skimmilk boiling at atmospheric pressure. This value corresponded to an initial heat flux $\frac{q}{A}$ of 9.8 cal sec^{-1}cm^{-2}, and ensured nucleate boiling on the wire. The temperature t of the wire increased gradually, which was caused by precipitation of coagula on the heating surface.

If a constant temperature t_O of the gradually increasing exterior surface of the coagulated layer is assumed, the growth of this layer can be estimated, and so can its thermal conductivity k_C, provided that the resultant wire diameter D_C is measured subsequently. The following expression applies here:

$$q = 2\pi k_C L \cdot \frac{t - t_O}{\ln D_C - \ln D} \qquad (4)$$

The result is shown in fig. 3, the increase in wire temperature $t - t_O$, and the growth of the exterior surface radius d being plotted as functions of time. The thermal conductivity of the coagulated layer k_C was calculated to approximately 6×10^{-4} cal sec^{-1}cm^{-1} °C^{-1}. Obviously the layer acted fairly well as an insulator. Only in this case the coagulation layer was composed of an almost solid substance, which had attained a yellowish colour.

HEAT FLUX TO SKIMMILK AND TO DILUTIONS OF SKIMMILK WITH WATER AT A PRESSURE OF 10 cm Hg

Fig. 4 shows the heat flux to boiling pasteurized skimmilk at a pressure of 10 cm Hg as a function of the difference in temperature between the heating

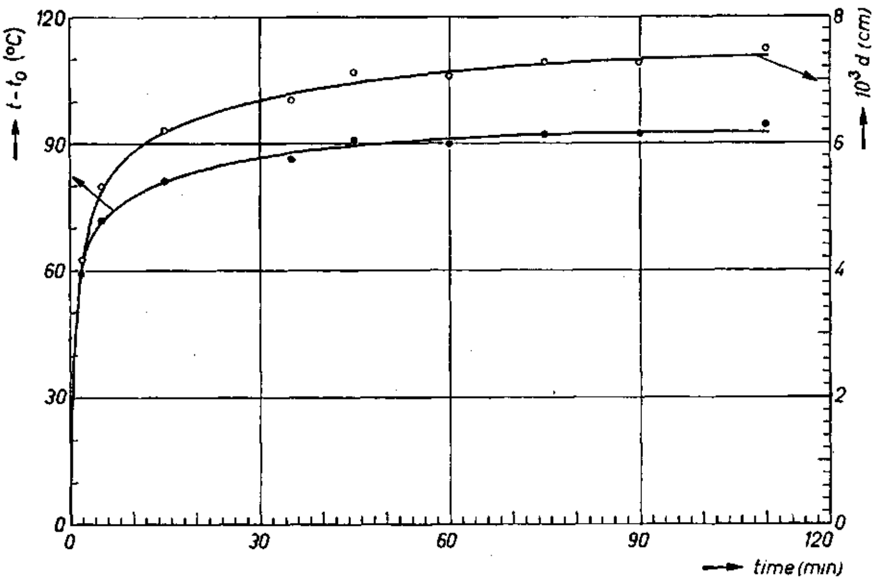

Fig. 3. Increase in temperature of heating wire and growth of coagulation layer at a constant nucleate boiling heat flow to skimmilk, boiling at atmospheric pressure.

t_0 denotes the initial temperature of wire and d denotes the average thickness of coagulation layer.

surface and the bulk of liquid. These data were determined with three different wires, and the results tallied satisfactorily (curve 1). At the same time a comparison was made made with the curve for water (curve 3) and with the data recorded for a dilution containing 3.2 % skimmilk in water (curve 2), both also at the same pressure.

Obviously the slope of the convection region was steeper for skimmilk than for water, as is shown in fig. 4, whilst the data for 3.2 % skimmilk tallied satisfactorily with the curve for water in this region.

The temperature of the wires increased rapidly, both for skimmilk and for 3.2 % skimmilk, when a heat flux value of 11 – 14 cal $sec^{-1}cm^{-2}$ was reached; apparently this had been caused by deposition of coagula on the heating surface. The wires burned out at a value of heat flux higher than the maximum of nucleate boiling to water, viz. at 28 and at 19 cal $sec^{-1}cm^{-2}$ respectively, comparing with 10 cal $sec^{-1}cm^{-2}$ for water. After burnout a small positive potential showing a gradual decrease could be recorded across the test section of the wire.

It should be stated here, that the values determined for Θ in the upper part of the region of nucleate boiling were calculated with respect to the initial reference value of resistance. These values cannot be considered to be quite exact, however, since the reference value had also been increased in this range.

With the object to ascertain that the upper part of the curves for skimmilk and for 3.2 % skimmilk belonged to the region of nucleate boiling, the heat flux to a dilution containing 0.7 % skimmilk in water was also studied at a pressure of 10 cm Hg. As a matter of fact in this case vapour bubbles on the heating surface could be observed, but burnout of the wire took place at the high value of 26 cal $sec^{-1}cm^{-2}$. Meanwhile a violent nucleate boiling had occurred, much more in-

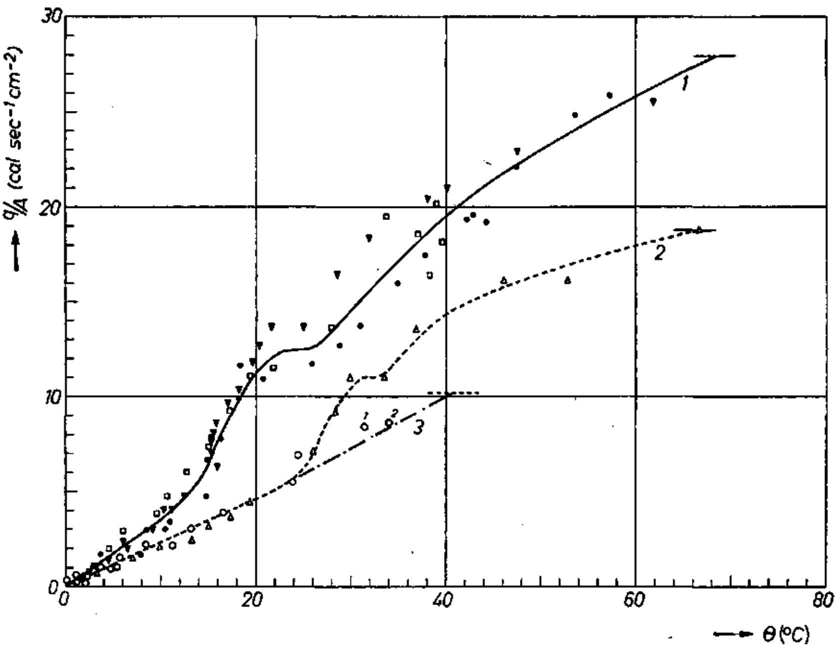

Fig. 4. Heat flux for convection and nucleate boiling to skimmilk (curve 1), to a dilution containing 3.2 % skimmilk in water (curve 2), and to water (curve 3) as a function of temperature difference between heating surface and liquid at a pressure of 10 cm Hg.
The figures at curve 3 denote the number of nuclei generating vapour bubbles.

tense than at the maximum for water, as not less than 10 active nuclei, generating smaller bubbles than with water, were observed.

In order to determine the effect of the deposition of coagula on the heating surface, the following experiment was carried out: A constant and sufficiently large heat flux was supplied to skimmilk, boiling at a pressure of 10 cm Hg. After some time the heating wire was contaminated to a certain extent by deposition of coagula. This wire burned out at the high value of 24 cal $sec^{-1}cm^{-2}$ in water, boiling at the same pressure, in contrast with the behaviour of a clean wire, which showed filmboiling at 11 cal $sec^{-1}cm^{-2}$ in the same water sample. Obviously the high maxima of nucleate boiling in skimmilk and in the samples of skimmilk diluted with water was caused by contamination of the heating surface by deposition of coagula.

HEAT FLUX TO WHEY AND TO DILUTIONS OF WHEY, OF LACTOSE AND OF A FOAMING AGENT WITH WATER

Fig. 5 shows the heat flux to whey (curve 1), and to a dilution containing 3.2 % whey in water (curve 2), in reference to the curve for water (curve 3). Again these curves were determined at a pressure of 10 cm Hg.

The curve for whey is practically identical to the curve for 3.2 % skimmilk (compare fig. 4). A rapid increase in precipitation of coagula on the heating surface occurred also in this case at a certain heat flux (12 cal $sec^{-1}cm^{-2}$), and the wires burned out at a relatively high average value of 24 cal $sec^{-1}cm^{-2}$.

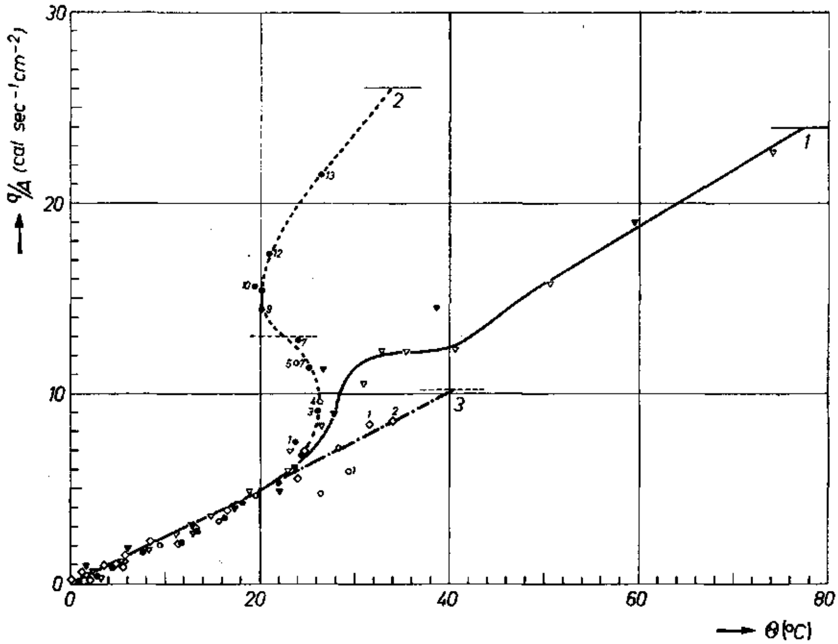

Fig. 5. Heat flux for convection and nucleate boiling to whey (curve 1), to a dilution containing 3.2 % whey in water (curve 2), and to water (curve 3) as a function of temperature difference between heating surface and liquid at a pressure of 10 cm Hg.
The figures at curves 2 and 3 denote the number of nuclei generating vapour bubbles.

For 3.2 % whey, the data of two different wires tallied satisfactorily if the heat flux did not exceed 13 cal $sec^{-1}cm^{-2}$. One of these wires, however, showed film-boiling at this value, which is slightly higher than the maximum of nucleate boiling in water, in accordance with the action of a larger number of nuclei, generating vapour bubbles. The other wire burned out at 26 cal $sec^{-1}cm^{-2}$. The average size of the bubbles gradually decreased, and a decrease in temperature of the wire occurred in the region of nucleate boiling. The wire was only slightly contaminated in this case, and apparently a favourable effect was shown by a very thin coagulation layer.

The presence of lactose seemed to have no direct influence on heat transfer, as can be concluded from the convection data for whey in fig. 5, which tallied fairly well with those for water (compare table 1 for composition of whey). Data for a solution containing 4.8 % wt of lactose in water, boiling at a pressure of 10 cm Hg, confirmed this conclusion, and corresponded fairly well with the curve for water (fig. 6).

Though the contamination of heating wires by deposition of coagula has been proved to be responsible for higher maxima of nucleate boiling in comparison with the value found for water, the influence of foaming was studied separately, also in connection with a publication of KIRSCHBAUM [5]. Rather stable foaming occurred namely with all concentrations of skimmilk and whey investigated.

The heat flux curves for a solution containing 1 % vol of a dilute foaming agent (teepol) in water, at atmospheric pressure and at a pressure of 10 cm Hg, are included in fig. 6. A result, similar to that for water, was obtained at a

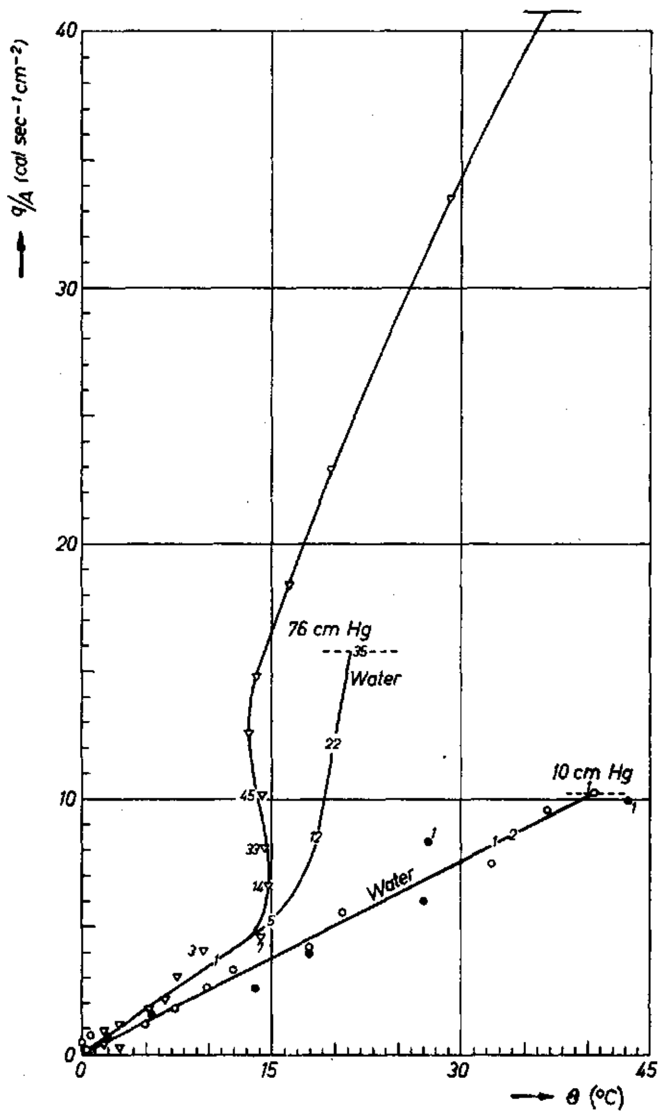

Fig. 6. Heat flux for convection and nucleate boiling to a solution containing 1 % vol of a dilute foaming agent in water (▽, ●) and to water, at atmospheric pressure and at a pressure of 10 cm Hg.

Heat flux for convection and nucleate boiling to a solution containing 4.8 % wt of lactose in water (○) at a pressure of 10 cm Hg.

The figures at the curves denote the number of nuclei generating vapour bubbles.

pressure of 10 cm Hg. Contrarily, however, a behaviour similar to that of 3.2 % whey was shown at atmospheric pressure (compare fig. 5). The heating wire was contaminated again, and burnout took place at the high value of heat flux of 41 cal $sec^{-1}cm^{-2}$. After burnout of the wire a small positive potential across the test section could be recorded also in this case. When the experiment was completed, the liquid had attained a yellowish colour, due to decomposition of the foaming agent. This phenomenon and the contamination of the heating surface did not occur, when a maximum of nucleate boiling equal to that for water, boiling at the same pressure, was determined rapidly for this solution with A.C. Obviously the increased maximum of nucleate boiling was once more caused by contamination of the heating surface only and not by the foaming properties of the boiling liquid. This seems to be in conflict with a statement of KIRSCHBAUM [5], who attributed higher heat transfer to foaming.

SURVEY AND DISCUSSION OF RESULTS

It has been shown in the preceding sections, that in principle a reproducible heat flux curve cannot be determined for skimmilk, boiling at atmospheric pressure, in consequence of a too rapid contamination of the heating surface (fig. 3). Apparently heat coagulation of milk constituents was much more prevalent at this pressure than at lower boiling temperatures, as reproducible results were obtained at a pressure of 10 cm Hg, at least in the region of convection, and in the lower part of the region of nucleate boiling.

The potential drop across the wire will have caused a gradually increasing contamination of the heating surface by all colloidal and dissociated constituents, in particular by proteins. It could be anticipated that this effect would be most pronounced with skimmilk and would be of leat importance for 3.2% whey, as the total amount of proteins was smallest in that case (see table 1). It is remarkable that, in contrast with the gradual course of this electrokinetic contamination, the temperature of the wire increased suddenly for skimmilk, 3.2% skimmilk and whey, when an average value of 78 °C was reached with a constant average heat flux of 12 cal $sec^{-1}cm^{-2}$ (figs. 4 and 5). Probably this critical value indicated the commencement of heat coagulation of lactalbumine and globuline. This presumption seems to be in accordance with several data published by LING in a textbook [6], where a temperature of 65 °C is mentioned for initial heat coagulation of these proteins, and heat coagulation of casein will occur above 100 °C.

TABLE 1. Composition of skimmilk and whey, according to LING [6].

	protein %	casein %	lactalbumine and globuline %	lactose %
skimmilk	3.7	3.2	0.5	5.0
3.2% skimmilk	0.115	0.1	0.015	0.15
whey	0.9	0.45	0.45	4.8
3.2% whey	0.03	0.015	0.015	0.15

With 3.2% whey – and also with a solution, containing 1% vol of a decomposing dilute foaming agent in water, boiling at atmospheric pressure – a similar increase in temperature of the wire at a certain value of heat flux did not occur, but on the contrary a gradually increasing slope of the curve is shown in the lower part of the region of nucleate boiling (figs. 5 and 6). According to table 1, this results seems to be in conflict with the different shape of the curve for 3.2% skimmilk, as both dilutions contained equal amounts of lactalbumine and globuline. The total amount of proteins, however, is much smaller in case of 3.2% whey, causing the heating surface to become less contaminated by electrokinetic

motions of colloidal particles. Slight contamination roughened the heating surface and increased the number of active vaporization nuclei, which was associated with a smaller average size of bubbles than with water, resulting in higher maxima of nucleate boiling. A favourable effect on the temperature of the heating surface by roughening was also found by JAKOB [2].

A small positive potential drop, showing a gradual decrease could be recorded across a contaminated wire, which had burned out at a high value of heat flux. This will be understood by considering the fact, that the colloidal particles present in skimmilk and whey were subjected to the action of the applied potential difference between the electrodes.

The coefficient of heat transfer for skimmilk exceeded considerably the value for water in the convection region (fig. 4). It may be worth noticing, that an explanation of this phenomenon on account of the physical properties of skimmilk seems to be impossible, as its viscosity is higher than of water. This feature represents an unfavourable factor, just as well as the somewhat lower thermal conductivity of skimmilk, according to measurements carried out by RIEDEL [7].

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SUMMARY

Heat flux for convection and nucleate boiling to several dilutions containing different amounts of milk constituents in water, was determined as a function of a difference in temperature between heating surface and bulk liquid. For that purpose electrically heated horizontal platinum wires were used acting at the same time as resistance thermometers. The behaviour of water, boiling at different pressures, was studied extensively in order to obtain suitable reference values. Attention was paid to the effect of pressure on the number of active nuclei, generating vapour bubbles on the heating surface, and also to the maximum of nucleate boiling in water.

When a constant nucleate boiling heat flow was supplied to pasteurized skimmilk, boiling at atmospheric pressure, a gradually increasing coagulation layer was precipitated on the heating wire, attended by a rapid decrease of the coefficient of heat transfer.

Hence restriction was made in the determination of heat flux data at a pressure of 10 cm Hg. Experiments were carried out with skimmilk, with whey and with dilutions, containing small amounts of either in water. Reproducible data were obtained in the region of convection and in the lower part of the region of nucleate boiling. High maxima of nucleate boiling occurred, considerably exceeding the maximum values recorded for water. This phenomenon could be attributed to a gradual contamination of the heating surface by deposition of coagula in consequence of the potential applied across the wire. In some cases

the temperature of the heating surface increased suddenly when a certain value of heat flux was reached. Probably this was due to heat coagulation of lactalbumine and globuline.

No special effect on heat transfer data exerted by lactose present in skimmilk and whey could be traced. The coefficient of heat transfer for skimmilk, however, exceeded considerably the value for water in the convection region. This increase was not present in whey and in the dilutions, containing small amounts of skimmilk or whey in water.

The behaviour of a solution, containing a small amount of a foaming agent in water, was studied separately, as rather stable foaming appeared in all concentrations of skimmilk and whey investigated. Except in case the wire had been contaminated due to a decomposition of the agent at atmospheric pressure, no increase in maximum nucleate boiling occurred.

REFERENCES

1. Burgess, G. K., and Chatelier, H. le, The measurement of high temperature, 3rd ed., John Wiley & Sons, New York 197, 493–495 (1912).
2. Jakob, M., and Fritz, W., Forsch. Gebiete Ingenieursw. **2**, 434–447 (1931).
3. McAdams, W. H., Heat transmission, 3rd ed., McGraw-Hill, New York/London 370 (1954).
4. McAdams, W. H., Addoms, J. N., Rinaldo, P. M., and Day, R. S., Chem. Eng. Progr. **44**, 639–646 (1948).
5. Kirschbaum, E., Dechema Monographien Nr. 250 **21**, 61–83 (1952); Chem. Ing. Technik **24**, 393–400 (1952).
6. Ling, E. R., A textbook of dairy chemistry, vol. I, Chapman & Hall, London 39–42, 106, 185 (1946).
7. Riedel, L., Chem. Ing. Technik **21**, 340–341 (1949).
8. Vos, A. S., and Stralen, S. J. D. van, Chem. Eng. Sci. **5**, 50–56 (1956).
9. Wijk, W. R. van, Vos, A. S., and Stralen, S. J. D. van, Chem. Eng. Sci. **5**, 68–80 (1956).
10. Stralen, S. J. D. van, Netherl. Journ. of Agric. Sci. **4**, 107–110 (1956).
11. Stralen, S. J. D. van, Chem. Eng. Sci. **5**, 290–296 (1956).

NOTATION

A	= area of surface of test section,	cm^2
B, C	= constants in temperature equation,	$°C^{-1}$, $°C^{-2}$
d	= thickness of coagulation layer on wire,	cm
D	= diameter of test section,	cm
D_C	= resultant exterior diameter of contaminated wire,	cm
E	= potential drop across test section,	V
h	$= \frac{q}{A\Theta}$ = coefficient of heat transfer in test section,	$cal\ sec^{-1} cm^{-2} °C^{-1}$
I	= electrical current strength through test section,	A
k	= thermal conductivity of platinum,	$cal\ sec^{-1} cm^{-1} °C^{-1}$
k_C	= thermal conductivity of coagulation layer on wire,	$cal\ sec^{-1} cm^{-1} °C^{-1}$
L	= length of test section,	cm
p	= pressure,	cm Hg
q	= heat flow in test section,	$cal\ sec^{-1}$
q/A	= heat flux in test section,	$cal\ sec^{-1} cm^{-2}$
R_T	= electrical resistance of test section at boiling temperature of liquid,	Ω
t	= temperature of test surface,	°C
t_0	= temperature of exterior area of coagulation layer on wire,	°C
T	= boiling temperature of liquid,	°C
Θ	$= t-T$ = difference in temperature between test surface and boiling liquid,	°C
$\varphi(T)$	= multiplication factor in equation on difference in temperature,	°C