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# A SIMPLIFIED MODEL OF THE BOILING CRISIS

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**Abstract** — An analytic model of flow boiling crisis in annular flow (at high vapor quality) and our experimental results of Freon 21 are presented in the paper. The model is based on the analysis of the film drying process on the channel wall, thus expressing the mass balance of both the film and the core by means of differential equations. The solution of these equations contains the parameters determined experimentally since their theoretical prediction involves serious difficulties.

## NOMENCLATURE

- $C$, parameter in the mass transfer equations;
- $c$, concentration of droplets in the flow core;
- $D$, mass flux of deposition;
- $d$, nondimensional mass flux of deposition $d = D/G$, channel diameter;
- $E$, mass flow of entrainment;
- $e$, nondimensional mass flux of entrainment $e = E/G$;
- $G$, mass flux of the main flow;
- $g$, nondimensional mass flux of the main flow;
- $K$, parameter in the mass transfer equations;
- $k$, mass transfer coefficient;
- $p$, pressure;
- $r$, latent heat of vaporization;
- $S$, nondimensional constant $S = \frac{Yz_{cr}}{2x_{cr}}$;
- $t$, nondimensional parameter $t = x_{cr}\frac{z^+}{z^+_{cr}}$;
- $V$, nondimensional specific volume $V = \frac{v_L}{v_G}$;
- $v$, specific volume;
- $X$, steam quality;
- $Y$, parameter;
- $z$, longitudinal coordinate;
- $z^+$, nondimensional longitudinal coordinate;
- $q$, heat flux;
- $q^+$, nondimensional heat flux.

Greek symbols

- $\rho$, specific density;
- $\sigma$, surface tension;
- $\mu$, dynamic viscosity;
- $\nu$, kinematic viscosity.

Subscripts

- $c$, droplet in the core;
- $E$, entrainment;
- $D$, deposition;
- $F$, film;
- $G$, gas;
- $j$, flow core;
- cr, boiling crisis, critical state;
- $L$, liquid;
- 0, beginning of the annular flow, channel diameter.

## INTRODUCTION

THE BOILING crisis phenomenon occurs in different technical devices, e.g. in nuclear reactors, steam generators, refrigeration evaporators etc. In the case of the high parameter equipment with two-phase vapor–liquid flow (boiling nuclear reactors, steam generators) the boiling crisis may involve serious damages due to the burn-out of the steam channels. In the low parameter steam generators, e.g. working on low boiling media, the crisis diminishes the heat transfer intensity and is not desirable for technical reasons.

Such generators are of increasing interest at the moment. Besides the refrigeration technology they are used in utilising the waste heat of chemical processes and will probably be applied in the new geothermal or solar plants with turbines working on the low-boiling media.

An order of investigations performed in the last fifteen years was concerned with the mechanism of the boiling crisis and the methods of its prediction. However, the satisfying solutions of this very complex problem have not yet been obtained. There exist practically no comprehensive analytic studies of the boiling crisis phenomenon except for some simple models. On the other hand one can find a substantial number of experimental data, mainly for water. Unfortunately, it is rather difficult to generalize them.

The boiling crisis in the annular flow at high steam quality forms a particular interest of technology. A characteristic parameter of that case of the crisis is the critical vapor quality $x_{cr}$.

The general theory of that phenomenon has not yet been worked out besides an order of hypotheses and partial theoretical investigations [1–3, 5–10].

The experimental results show a substantial scatter [7]. The data presented by different authors concerned mainly particular cases suggested by the temporal needs of the industry.

Recently a more general theoretical model of the boiling crisis based on the film dry-out process on the channel wall during annular flow has been proposed [3, 4]. The model involves a complex computer procedure but gives fairly good results for water and other media, e.g. Freon 12.

In this paper an analytic model of the boiling crisis at high vapor quality and the authors' investigations of that phenomenon are presented. The model employs the analysis of the film dry-out process on the wall which allows formulation of the differential equations of mass balance in the film and the core. The solution of these equations contains the parameters which are determined experimentally in this paper since their theoretical prediction involves serious difficulties.

## THE THEORETICAL MODEL OF THE FLOW BOILING CRISIS

Let us consider the two-phase annular flow of the mass flux $G$ in the circular channel of the internal diameter $d_0$. The liquid film covers the channel wall and the vapor, with suspended droplets of liquid, flows in the core (Fig. 1). The beginning of the annular flow pattern is assumed to be known and from that point the mass balancing starts. As a criterion of the crisis occurrence the film dry-out on the wall is assumed, however, recent investigations [10] suggest the film breakdown into rivulets rather than its entire evaporation. For the sake of simplicity it is assumed that the crisis occurs at the film flow rate equal to zero. This simplification was justified in [11].

The mass flux of evaporation from the film surface due to the wall heat flux $q$, is equal to $q/r$. This process is accompanied by the droplet entrainment from the film surface $E$ and the droplet deposition onto the film surface $S$ (see Fig. 1). In accordance with the model assumed, the elementary mass changes of the film and the core, $dG_F$ and $dG_E$, respectively, are

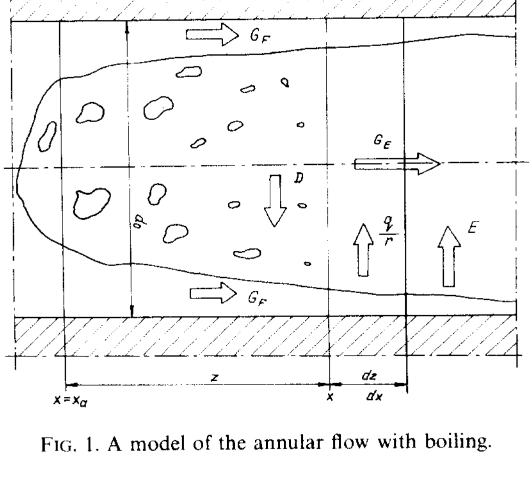


FIG. 1. A model of the annular flow with boiling.

$$\frac{dG_F}{dz} = \frac{4}{d_0}\left(D - E - \frac{q}{r}\right)$$

$$\frac{dG_E}{dz} = \frac{4}{d_0}(-D + E),$$

or in dimensionless form

$$\frac{dg_F}{dz^+} = 4(d - e + q^+) \tag{1a}$$

$$\frac{dg_F}{dz^+} = 4(-d + e), \tag{1b}$$

where

$$d = \frac{D}{G};\ e = \frac{E}{G};\ q^+ = \frac{q}{rG};\ z^+ = \frac{z}{d_0}.$$

In order to solve the set of equations (1a, b), the fluxes $d$ and $e$ must be known. It was assumed

$$e = K \cdot C \cdot g_F \tag{2}$$

$$d = C \cdot g_E, \tag{3a}$$

where $K$ and $C$ are the parameters not exactly defined at the moment.

According to [3] the mass flux $d$ may be expressed by

$$d = \frac{k \cdot c_i}{G}, \tag{3b}$$

when $k$ is the mass transfer coefficient and $c_j$ stands for the concentration of liquid within the core and may be determined after [5]

$$c_j = \frac{1 - x_j}{(1 - x_j)v_L + x_j \cdot v_G}. \tag{4}$$

Steam quality within the flow core in equation (4) is defined as follows

$$x_j = \frac{G_G}{G - G_F} = \frac{1 - g_E - g_F}{1 - g_F}. \tag{5}$$

The general formula describing the mass transfer coefficient $k$ given in [12] is

$$k = c_k \frac{G^n}{d_0^m}(1 - g_F - g_E)^n, \tag{6}$$

where $C_k$ is a function of the fluid properties and the two-phase flow characteristics ($v_G$, $\mu_G$, $T$, $\rho_c$, $v_c$, $d_c$, ...) and $m, n$ are not exactly known exponents.

Combining equations (2), (3a, b) (4) and (6) one gets as a result

$$d = c_k' \cdot \frac{g_E(1 - g_F - g_E)^n}{g_E v_L + (1 + g_F - g_E)v_G} \tag{7}$$

and

$$e = K \cdot C_k' \frac{g_F(1 - g_F - g_E)^n}{g_E v_L + (1 + g_F - g_E)v_G}, \tag{8}$$

where

$$C'_k = C_k \frac{G^{n-1}}{d_0^m}. \tag{9}$$

Ultimately, a set of nonlinear differential equations describing the dimensionless mass fluxes within the film and the core was obtained from equations (1a, b), (7) and (8)

$$\frac{\mathrm{d}g_F}{\mathrm{d}z^+} = 4\left[C'_k \frac{g_E(1-g_F-g_E)^n}{g_E v_L + (1+g_E-g_F)v_G} - K \cdot C'_k \frac{g_F(1-g_F-g_E)^n}{g_E v_L + (1-g_E-g_F)v_G} - q^+\right] \tag{10a}$$

$$\frac{\mathrm{d}g_E}{\mathrm{d}z^+} = 4\left[-C'_k \frac{g_E(1-g_F-g_E)^n}{g_E v_L + (1+g_E-g_F)v_G} + K \cdot C'_k \frac{g_F(1-g_F-g_E)^n}{g_E v_L + (1-g_E-g_F)v_G}\right]. \tag{10b}$$

Rearranging the equations (10a, b) one gets the first-order nonlinear differential equation for the film mass flux

$$\frac{\mathrm{d}g_F}{\mathrm{d}t} = S \cdot \frac{(1-g_F-g_E)^n(g_E - K \cdot g_F)}{g_E V + (1-g_E-g_F)} - 1, \tag{11}$$

where

$$t = x_{\mathrm{cr}} \cdot \frac{z^+}{z^+_{\mathrm{cr}}}, \tag{12}$$

$$S = \frac{4z^+_{\mathrm{cr}} c'_k}{x_{\mathrm{cr}} v_G} = \frac{Y \cdot z_{\mathrm{cr}}}{2x_{\mathrm{cr}}}, \tag{13}$$

$$V = \frac{v_L}{v_G}, \tag{14}$$

and

$$q^+ = \frac{x_{\mathrm{cr}} - x_0}{4z^+_{\mathrm{cr}}} \cong \frac{x_{\mathrm{cr}}}{4z^+_{\mathrm{cr}}}. \tag{15}$$

According to Hewitt [3] it was recognized that the annular flow pattern surely exists at the steam quality equal to 0.01 and if the share of the film flow is about 0.01 of the total mass flow rate of the liquid phase. Numerical predictions performed by Hewitt *et al.* revealed the method to be slightly sensitive to small deviations of the initial steam quality from the value of 0.01.

Equation (11) cannot be solved analytically and, hence, a numerical method was used. As a result the function of the critical steam quality $x_{\mathrm{cr}}$ vs the nondimensional coordinate $Yz_{\mathrm{cr}}$ for selected values of $K$, $n$ and $V$ was obtained. The results are shown in Fig. 2. Additionally, the Appendix presents the solution of equation (11) for the case, when various values of film flow rate at the beginning of the annular flow and at the end, when the crisis occurs, are taken into account. Calculation results are shown in Fig. A1. For the sake of comparison the results of the analytic solution of the simplified form of equation (11) with assumption of $n = 1$ and $V \cong 0$ are presented in Fig. 2. The above simplifications allow direct determination of the steam quality in the cross section of crisis (where the film disappears) as a function of nondimensional coordinate of boiling $Yz_{\mathrm{cr}}$.

$$x_{\mathrm{cr}} = \frac{0.99\,e^A - (0.98 - 0.01\,K)}{\frac{K}{A}(e^A - 1) + e^A} \cong \frac{1}{\frac{K}{A} + \frac{e^A}{e^A - 1}}, \tag{16}$$

where

$$A = \frac{1+K}{2} Yz_{\mathrm{cr}}.$$

For large values of $K$ equation (16) takes a simpler form

$$x_{\mathrm{cr}} = \frac{1}{1 + 2/Yz_{\mathrm{cr}}} \tag{16a}$$

similar to that determined experimentally by Silvestri [6].

It is seen from Fig. 2 that the analytic solution of the simplified form of equation (11) given by equation (16) is similar to the numerical solution of exact equation

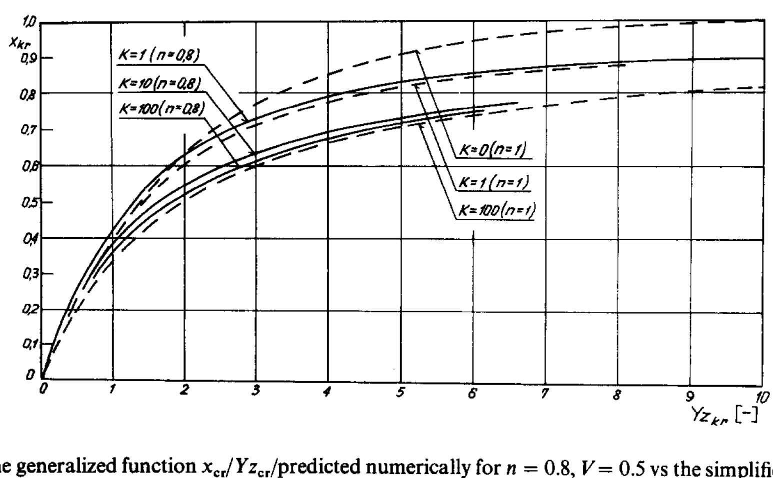


FIG. 2. The generalized function $x_{\mathrm{cr}}/Yz_{\mathrm{cr}}/$predicted numerically for $n = 0.8$, $V = 0.5$ vs the simplified analytic solution for $n = 1$, $V = 0$ after equation (16).

(11). The further analysis is continued with the simplified model described by equation (16).

The parameter $Y$ has a dimension $[m^{-1}]$ and, as it follows from the analysis performed in [12], is a function of the typical parameters influencing the crisis: mass flux $G$, channel diameter $d_0$, viscosity of the gas phase $\mu_G$, specific volume of the gas phase $v_G$ etc.

Analytic determination of $Y$ for given crisis conditions is rather difficult and it seems most reasonable to correlate that parameter on the experimental basis. The same stands for the parameter $K$ in the formula for the mass transfer of entrainment $e$.

In order to determine both of these parameters an experimental apparatus was built and the experiments with Freon 21 performed.

## THE EXPERIMENTAL INVESTIGATIONS OF FREON 21

The experimental investigations were aimed at the verification of the analytic model presented in this paper and, in consequence, at correlating the parameters $Y$ and $K$ in the analytic solution (16).

The experiments were carried out with Freon 21 on the test apparatus schematically shown in Fig. 3. The test section was a stainless steel tube 4.220 m in length and 0.008 m in internal diameter. The boiling crisis appearing in the experiments as a steep rise of the wall temperature in the upper part of the test section was detected and continuously recorded by several thermocouples attached directly to the wall.

Moreover, other important parameters, i.e. temperatures, pressures and electric power supplied to the test section and to the heater were also recorded.

The moment of the boiling crisis appearance was accompanied by increasing pressure oscillations and falling flow rate of the fluid. When the wall temperature was rising above a certain fixed value (from 150 to 250°C) a special crisis detector switched off heating. The experiments were carried out for the pressures of 5.5, 10.6 and 15.0 bar for three selected mass fluxes of 1000, 1750 and 3500 kg/m²/s.

From these experiments the dependence of the critical vapor quality $x_{cr}$ vs the boiling section length $z_{cr}$ was established. The length of the boiling section was determined from the heat balance with an additional assumption of $x_0 = 0.01$ at the beginning of the annular flow pattern. Subsequently, the curves predicted from the analytic model [equation (16)] were fitted to the experimental points using the least squares technique.

Therefore, as a result of optimization computations based on equation (16) the best values of the parameters $K$ and $Y$ were obtained. It was established that the parameter $K$ for Freon 21 varies between 16 and 26 and may be assumed to be a constant equal to 20. Such an assumption slightly affects the analytic curve (16) and substantially simplifies further considerations.

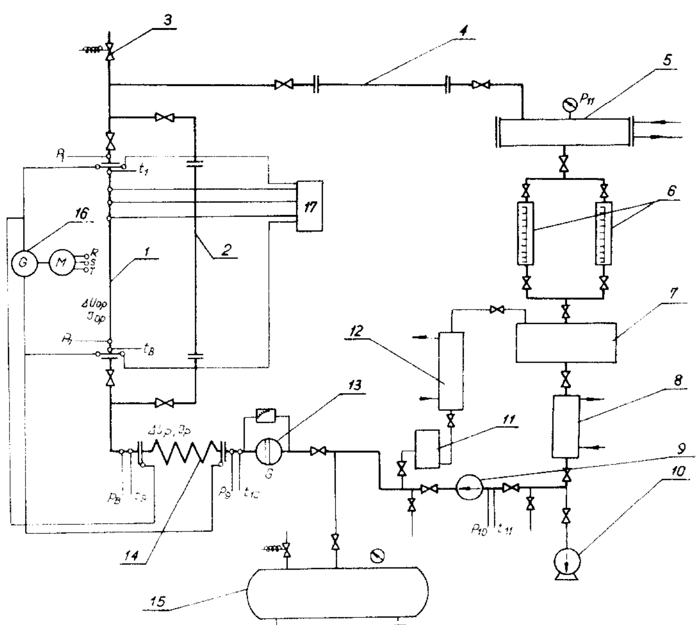


FIG. 3. Layout of the experimental apparatus for the boiling crisis investigations. 1. vertical test section, 2. by-pass, 3. safety-valve, 4. horizontal test section, 5. condenser, 6. condensate measurement tank, 7. equalizing tank, 8. cooler, 9. circulation pump, 10. vacuum pump, 11. filter, 12. by-pass cooler, 13. orifice plate, 14. heater, 15. main tank, 16. DC generators, 17. crisis detector, $P_1$ and $P_{11}$, pressure measurements, $t_1$ and $t_8$, wall temperature measurements of the test section, $t_9$ and $t_{10}$, working fluid temperature measurements, $G$, mass flow rate measurements, $\Delta U_{0p}$, $I_{0p}$, voltage and current measurement of the test section, $\Delta U_p$, $I_p$, voltage and current measurement of the heater.

It was mentioned before that the parameter $Y$ is the following function

$$Y = Y(G, p, d_0, \ldots). \qquad (17)$$

Moreover, this parameter may be affected by the other properties, not expressed in equation (17), but influencing deposition of entrainment process, e.g. surface tension $\sigma$. Dimensional analysis of $Y$ provides the nondimensional number $Yd$ dependent on the two-phase flow criterial numbers. The following expression for $Yd_0$ is proposed:

$$Yd_0 = A\left(\frac{Gd_0}{\mu_G}\right)^b \left(\frac{\rho_L \sigma d_0}{\mu_G^2}\right)^{b_1} \cdot f\left(\frac{p}{p_{cr}}\right). \qquad (18)$$

The constants $A$, $b$ and $b_1$ and the form of the function $f(p/p_{cr})$ were determined from the experiments with Freon 21 so that the following formula for $Yd_0$ was obtained:

$$(Yd_0)_{F\text{-}21} = 1.27 \cdot 10^6 \left(\frac{Gd_0}{\mu_G}\right)^{-1.40} \cdot \left(1 - 1.9\frac{p}{p_{cr}}\right). \qquad (19)$$

In the experiments with Freon 21 the mass flux $G$ and the pressure $p$ were variable and the channel diameter $d_0$ was constant.

The comparison of the critical vapor quality $x_{cr}$ predicted from equation (16) with regard to equation (19) against the experimental results is shown in Fig. 4, from which it follows that 74% of the experimental points lie within the error limit of $\pm 10\%$ and all of them within $\pm 25\%$ error.

## THE COMPARISON OF THE EXPERIMENTAL RESULTS FOR FREON 21 AND FREON 12

For the sake of comparison the predictions after the model described here were carried out for the experiments with Freon 12 performed by Stevens [6].

Freon 12 is thermodynamically similar to Freon 21. On the base of the computed best values of $K$ and $Y$ the critical vapor quality $x_{cr}$ ($z_{cr}$) was predicted after equation (16) and the results shown in Figs. 5–7.

The results of predictions are in a very good agreement with the experiments, particularly at lower mass fluxes.

In the experiments mentioned above the mass flux $G$ and the tube diameter $d_0$ varied ($d_0 = 5.3$, 8.5, $16.1 \times 10^{+3}$ m) and the pressure was kept constant. Relevant formula for $Y$ for Freon 12 takes the form:

$$(Yd_0)_{F\text{-}12} = 1.805 \cdot 10^{-3}\left(\frac{\rho_L \sigma d_0}{\mu_G^2}\right)^{1.17}\left(\frac{Gd_0}{\mu_G}\right)^{-1.60}, \qquad (20)$$

where $K$ takes similar values as before and was also assumed to be equal to 20.

The comparison of the experimental results of Freon 12 with the predictions made after equation (16) with regard to equation (20) shows most of the points lying within error limits of $\pm 15\%$.

## CONCLUSIONS

The method presented seems to allow the fairly accurate predictions of the flow boiling crisis parameters and, at the same time, is expressed by the relatively simple analytic formulas.

The correlations established for $K$ and $Y$ [equations (19), (20)] are, at the moment, specific for each medium.

It is hoped that continued theoretical and experimental research will result in a more precise identification and determination of these parameters and, possibly, general relationship valid for different media will be produced.

This paper is to be understood as a proposal of the reduction of experimental data. It also gives an insight into the flow boiling crisis phenomenon basing on its physical model.

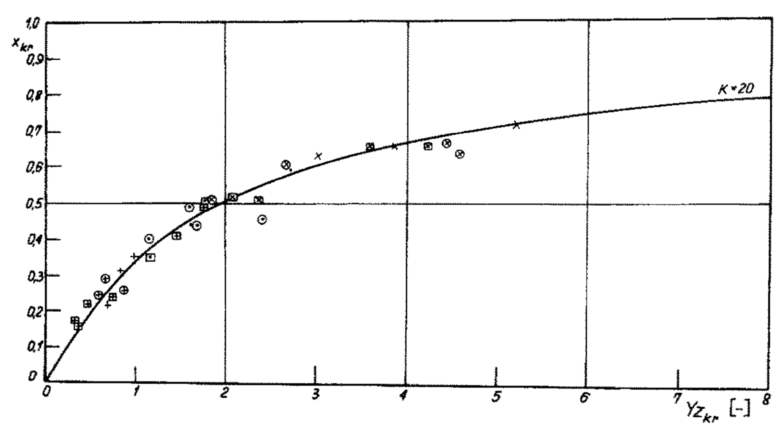


FIG. 4. Critical vapor quality $x_{cr}$ vs nondimensional critical boiling length $Yz_{cr}$ after (16) and (20) in comparison with the experiment for Freon 21. ($d_0 = 0.008\,m$, $p = 5.5$, 10.6, 15.0 bar). ×, ·, +—$G$ = 1000, 1750, 3500 kg/m² s, $p = 5.5$ bar; ⊗, ○, ⊕—$G$ = 1000, 1750, 3500 kg/m² s, $p = 10.6$ bar; ⊠, ⊡, ⊞—$G$ = 1000, 1750, 3500 kg/m² s, p = 15.0 bar.

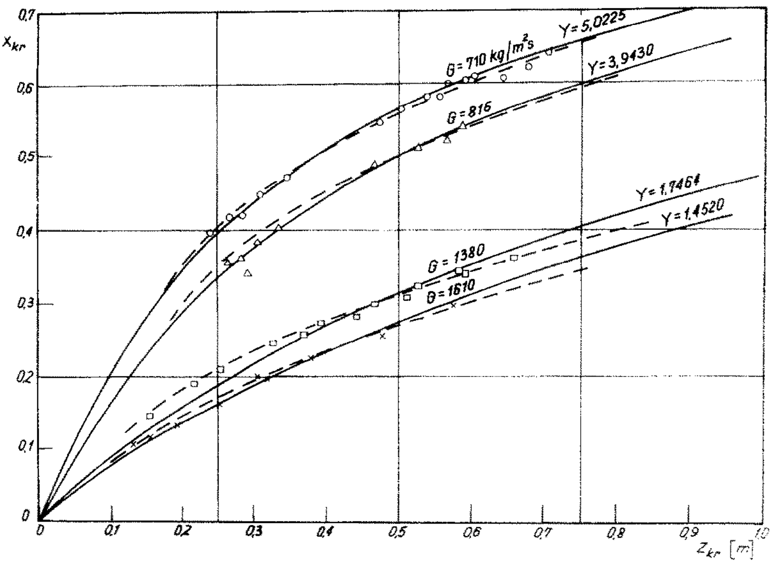


FIG. 5. Experimental results of the boiling crisis investigations of Freon-12 [6]. $p$ = 10.6 bar, $d_0$ = 0.053 m; ○—$G$ = 710 kg/m² s, △—$G$ = 815 kg/m² s, □—$G$ = 1380 kg/m² s, ×—$G$ = 1610 kg/m² s; - - - —— wg [6], ——— — wg (16).

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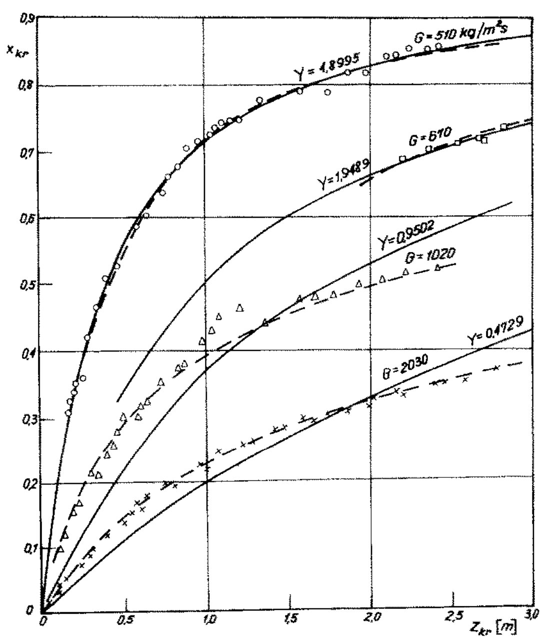


FIG. 6. Experimental results of the boiling crisis investigations of Freon [6]. $p$ = 10.6 bar, $d_0$ = 0.0085 m, ○— = 510 kg/m² s, □—$G$ = 670 kg m² s, △—$G$ = 1020 kg/m² s, ×—$G$ = 2030 kg/m² s, (— — —)—wg [6], (———)—wg (16).

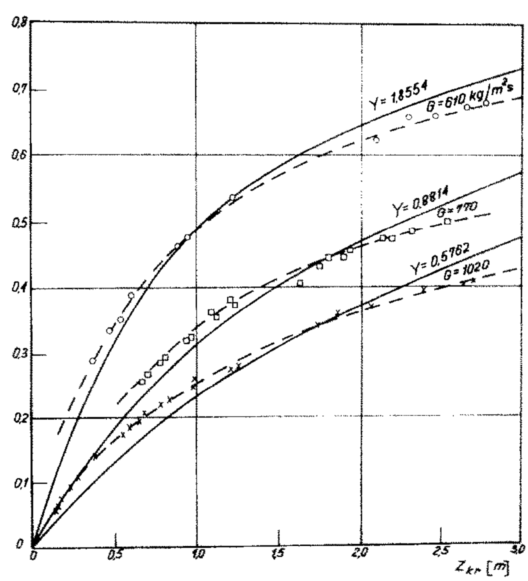


FIG. 7. Experimental results of the boiling crisis investigations of Freon 12 [6]. $p$ = 10.6, $d_0$ = 0.0161 m, ○—$G$ = 510 kg/m² s, □ — $G$ = 770 kg/m² s, × — $G$ = 1020 kg/m² s, (— — —) — wg [6], (———) — wg (16).

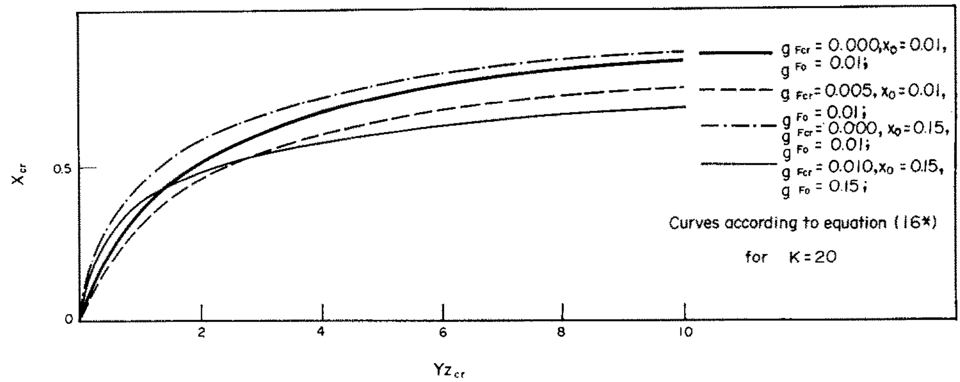


FIG. A1.

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## APPENDIX

Let the equation (11) take the following form

$$\frac{dg_F}{dt^*} = S^* \frac{(1 - g_F - g_E)^n (g_E - kg_F)}{g_E V + 1 - g_E - g_F} - 1, \qquad (11^*)$$

where

$$t^* = (x_{cr} - x_0)\frac{z^+}{z^+_{cr}} \qquad (12^*)$$

$$S^* = \frac{4z^+_{cr} c'_k}{(x_{cr} - x_0)V_G} = \frac{Yz_{cr}}{2(x_{cr} - x_0)} \qquad (13^*)$$

$$q^+ = \frac{x_{cr} - x_0}{4z^+_{cr}}, \qquad (15^*)$$

the other quantities remaining the same. Then taking

$$n = 1, \quad V = 0,$$

the initial conditions being

$$z^+ = 0; \quad g_F = g_{F_0}$$

and the crisis conditions being

$$z^+ = z^+_{cr}; \quad g_F = g_{F_{cr}},$$

the equation (16) takes the following general form

$$x_{cr} = \frac{[1 - g_{F_{cr}}(1 + K)]e^A + [x_0 + g_{F_0}(1 + K) - 1] + K/Ax_0(e^A - 1)}{K/A(e^A - 1) + e^A}, \qquad (16^*)$$

where

$$A = \frac{Yz^+_{cr}(1 + K)}{2},$$

$g_{F_0}$—initial film flowrate,
$x_0$—initial quality,
$g_{F_{cr}}$—film flowrate at crisis conditions,

the other quantities being equivalent to those in equation (16). The influence of the quantities $g_{F_0}$, $x_0$, $g_{F_{cr}}$, shows Fig. A1.

## UN MODELE SIMPLIFIE DE L'EBULLITION CRITIQUE

**Résumé**—On présente un modèle analytique de l'ébullition critique avec écoulement dans un espace annulaire/avec titre élevé de vapeur/et des résultats expérimentaux sur le Fréon 21. Le modèle s'appuie sur l'analyse du mécanisme de l'assèchement du film sur la paroi du canal et sur l'expression du bilan massique du film et du noyau au moyen d'équations différentielles.

La solution de ces équations contient les paramètres déterminés expérimentalement car leur estimation théorique soulève de sérieuses difficultés.

## EIN EINFACHES MODELL DER SIEDEKRISE

**Zussammenfassung** — Es wird über ein analytisches Modell der Siedekrise bei Ringströmung mit großen Dampfgehalten und über eigene experimentelle Ergebnisse mit Freon 21 berichtet. Das Modell basiert auf der Berechnung des Austrocknungsprozesses des Films an der Kanalwand, wobei die Massenbilanz für den Film und die Kernströmung mit Hilfe von Differentialgleichungen bestimmt wird. Die Lösung dieser Gleichungen enthält experimentell bestimmte Parameter, da deren theoretische Bestimmung mit großen Schwierigkeiten verbunden ist.

## УПРОЩЕННАЯ МОДЕЛЬ КРИЗИСА КИПЕНИЯ

**Аннотация** — Предложена аналитическая модель кризиса кипения при течении жидкости в кольцевом канале (при больших паросодержаниях) и представлены экспериментальные данные по кипению фреона 21. Модель, разработанная исходя из анализа процесса высыхания пленки на стенке канала, основана на балансе потоков массы в пленке и ядре, представленном в виде дифференциальных уравнений. В решение этих уравнений входят экспериментально определяемые параметры, теоретический расчет которых представляет серьёзные трудности.