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Assessment of correlations and models for the prediction of CHF in water subcooled flow boiling

G. P. CELATA, M. CUMO and A. MARIANI

ENEA, Thermal Process Engineering Division, Viá Anguillarese, 301, I-00060 Rome, Italy

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Abstract—The present paper provides an analysis of available correlations and models for the prediction of Critical Heat Flux (CHF) in subcooled flow boiling in the range of interest of fusion reactors thermal-hydraulic conditions, i.e. high inlet liquid subcooling and velocity and small channel diameter and length. The aim of the study was to establish the limits of validity of present predictive tools (most of them were proposed with reference to LWR thermal-hydraulic studies) in the above conditions. The reference data-set represents almost all available data (1865 data points) covering wide ranges of operating conditions in the frame of present interest ($0.1 < p < 8.4$ MPa; $0.3 < D < 25.4$ mm; $0.1 < L < 0.61$ m; $2 < G < 90.0$ Mg m^{-2} s^{-1}; $90 < \Delta T_{sub,in} < 230$ K). Among the tens of predictive tools available in literature four correlations (Levy, Westinghouse, modified-Tong and Tong-75) and three models (Weisman and Ileslamlou, Lee and Mudawar and Katto) were selected. The modified-Tong correlation and the Katto model seem to be reliable predictive tools for the calculation of the CHF in subcooled flow boiling.

INTRODUCTION

As is known [1–4], the removal of high heat fluxes as required by fusion reactor thermal-hydraulics, may be achieved by making use of highly subcooled water flow boiling at high liquid velocity. As successful use of this technique requires the critical heat flux (CHF) to be avoided, it is necessary, in addition to the availability of experimental data for the understanding of the phenomenon, to have CHF prediction tools for calculation and design purposes. Scarcity of experimental data in the range of interest for fusion reactor thermal-hydraulics implies also a lack of suitable correlations for the prediction of subcooled CHF. Available correlations for the prediction of the CHF in subcooled flow boiling were recommended in ranges of pressure, liquid velocity and subcooling, and consequently heat fluxes, typical of the Light Water Reactors (LWR), i.e. much different than those required for the cooling of the high heat flux components of the fusion reactor. In the case of LWRs the heat flux to be removed is, as an order of magnitude, around 1 MW m^{-2}, while in the case of fusion reactors some components may require heat fluxes up to 60 MW m^{-2} to be removed. Nonetheless, it is known that correlations cannot be used in a reliable way outside the range recommended by authors. On the other hand, the absence of suitable experimental data and visual information that could clarify the basic mechanisms of subcooled flow boiling under these conditions does not allow a full understanding of the phenomenon so to enable an actual mechanistic description of the phenomenon itself in a model.

The aim of the present paper is to provide an assessment of what is available in the literature, both in terms of correlations and in terms of models, against most of the experimental data existing in the literature in the range of interest of fusion reactors. The result is the definition of the bounds of reliability of the existing prediction tools. To this purpose, among the tens of correlations available, results are reported here only for those providing a consistent prediction of most of the data set, namely Levy [5], Westinghouse [6], modified-Tong [7] and Tong-75 [8] correlations. The three existing models proposed by Weisman–Ileslamlou [9], Lee-Mudawar [10] and Katto [11] were reported. It must be pointed out here that the above correlations (with the only exception of the modified-Tong correlation) and models (with the exception of the Katto model) are tested in the present study against experimental data whose operating ranges are outside the recommended ones. Therefore, possible inaccuracy of prediction is not to be ascribed to a weakness of the single correlation or model, but only to the misuse of them (out of range). The purpose of their use in the present comparative study is only to check the possibility of extending the validity range of existing correlations and models to have predictive tools in the range of interest of fusion reactor thermal hydraulics. As far as data sets are concerned [12–36] they cover the following operating ranges: $0.1 < p < 8.4$ MPa; $0.3 < D < 25.4$ mm; $0.1 < L < 0.61$ m; $2 < G < 90.0$ Mg m^{-2} s^{-1}; $90 < \Delta T_{sub,in} < 230$ K.

AVAILABLE EXPERIMENTAL DATA

Subcooled flow boiling CHF was extensively studied in the past [37–39] in a range of interest for LWRs, that refers to conditions very far from fusion reactor thermal-hydraulics requirements (heat flux up to 60

NOMENCLATURE

Bo	boiling number, $q''/G\lambda$
C	parameter defined in (3), (4) and (6)
CHF	critical heat flux [W m^{-2}]
C_p	specific heat [J kg^{-1} K^{-1}]
D	channel diameter [mm]
D_0	reference diameter, $D_0 = 0.0127$ m
D_e	test section equivalent internal diameter [mm]
F	parameter defined in (1)
f_0	parameter defined in (7)
G	mass flux [kg m^{-2} s^{-1}]
g	gravitational acceleration [m s^{-2}]
h	enthalpy [J kg^{-1}]
h_l	heat transfer coefficient [W m^{-2} K^{-1}]
Ja	Jacob number, $C_p(T_b - T_{sub})\rho_f/\lambda\rho_g$
K	thermal conductivity [W m^{-1} K^{-1}]
k	velocity coefficient
L	channel length [cm]
L_B	vapour blanket length [μm]
Pr	Prandtl number, $C_p\mu/K$
p	pressure [MPa]
q''	heat flux
Re	Reynolds number, GD/μ
T, ΔT	temperature, temperature difference [°C, K]
U_B	vapour blanket velocity [m s^{-1}]
U_δ	liquid sublayer velocity as δ [m s^{-1}]
x	thermal equilibrium quality.

Greek symbols

α	void fraction
δ	liquid sublayer thickness [μm]
λ	latent heat [J kg^{-1}]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
Ψ	parameter defined in (6).

Subscripts

b	pertains to bulk conditions
CHF	pertains to burnout conditions
conv	convective
crit	critical (thermodynamic) conditions
ex	exit
f	pertains to the liquid in saturated conditions
g	pertains to the vapour
in	inlet
l	pertains to the liquid
out	outlet
pb	pool boiling
sat	saturated conditions
sub	subcooled conditions
w	pertains to the wall.

MW m^{-2}, mass flux up to 40 Mg m^{-2} s^{-1}, inlet subcooling up to 200 K, pressure up to 5.0 MPa, L/D from 10 to 200). In the recent past several researches were initiated to achieve a deeper understanding of subcooled flow boiling process.

Experimental points which will be used here to assess the available predictive tools are those presented by Boyd [12–14], Inasaka and Nariai [15], Nariai *et al.* [16], Achilli *et al.* [17], Celata *et al.* [18–21], Gambill and Greene [22], Vandervort *et al.* [23], Loosmore and Skinner [24], Ornatskii and Vinyarskii [25], Ornatskii and Kichigan [26], Ornatskii [27], Knoebel *et al.* [28], Mirshak *et al.* [29], Babcock [30], Burck and Hufschmidt [31], Mayersak *et al.* [32], Schaefer and Jack [33], Thorgerson [34], Zeigarnik *et al.* [35], and Gambill *et al.* [36]. The ranges of operating conditions for the data considered to establish correlations and models are summarized in Table 1, while a graphic representation of the overall operating range is given in Fig. 1 ($0.1 < p < 8.4$ MPa; $0.3 < D < 25.4$ mm; $0.0025 < L < 0.61$ m; $2 < G < 90.0$ Mg m^{-2} s^{-1}; $90 < \Delta T_{sub,in} < 230$ K). The total number of data points used in the present study is 1865.

AVAILABLE CORRELATIONS

A rich review of correlations for subcooled flow boiling CHF was given by Boyd [4], and many of them were tested by Celata [1, 40] and by Nariai and Inasaka [41]. Among the tens of correlations tested in [1, 40, 41], attention has been paid here only to those providing a consistent prediction of experimental data, so as to make possible an extension of their validity bounds. The correlations considered in the present calculations are: Levy [5], Westinghouse [6], modified-Tong [7] and Tong-75 [8] correlations.

Levy [5]:

$$q''_{CHF} = q''_{pb} + q''_{conv} + F \quad (1)$$

$$q''_{pb} = 0.131\lambda\rho_g\left[\frac{\sigma g^2(\rho_l - \rho_g)}{\rho_g^2}\right]^{1/4}$$

$$q''_{conv} = 0.696(K\rho_l C_p)^{1/2}\left(\frac{\rho_l - \rho_g}{\sigma}\right)^{1/4} \times \left[\frac{\sigma g^2(\rho_l - \rho_g)}{\rho_g^2}\right]^{1/8}\Delta T_{sub}$$

$$F = h_l(T_w - T_{sat}) + h_l\Delta T_{sub}$$

$$T_w - T_{sat} = \frac{60}{e^{p/900}}\left(\frac{q''}{10^6}\right)^{1/4}$$

$$h_l = 0.023\frac{K}{D}Re^{0.8}Pr^{1/4}$$

Table 1. Experimental data used for present calculation

CHF Data [ref.]	No. of points	T_{in} [°C]	p [MPa]	D [mm]	L [mm]	G [Mg m^{-2} s^{-1}]	q''_{CHF} [MW m^{-2}]
Celata *et al.* [18]	43	18.6–54.6	0.1–2.2	2.5, 4, 5	100	2.2–32.6	4.0–42.7
Celata *et al.* [19]	88	29.8–70.5	0.6–2.6	2.5	100	10.1–40.0	12.1–60.6
Celata *et al.* [21]	48	29.3–71.5	0.5–2.6	4.0	100	5.0–40.0	10.6–54.4
Celata *et al.* [21]	7	29.3–40.7	0.8	5.0	100	4.1–20.0	13.0–34.7
Celata *et al.* [20]	14	29.8–75.9	2.1–5.0	6.0	100	5.0–10.0	11.8–27.8
Celata *et al.* [20]	46	29.1–80.7	0.4–5.0	8.0	100–150	2.0–10.0	7.4–29.5
Inasaka–Nariai [15]	29	25.0–78.0	0.3–1.1	3.0	100	4.3–30.0	7.3–44.5
Nariai *et al.* [16]	95	15.4–64.0	0.1	1.0–3.0	10–100	6.7–20.9	4.6–70.0
Boyd [12–14]	10	20.0	0.77–1.66	3.0	289.7	4.4–40.5	6.0–41.5
Achilli *et al.* [17]	35	26.4–158.2	1.0–5.5	8.0–15.0	150–300	4.6–14.9	11.0–35.6
Gambill–Greene [22]	7	4.9–35.8	0.1	7.8	45–157	13.0–26.0	15.8–33.0
Vandervort *et al.* [23]	210	6.4–84.9	0.1–2.3	0.3–2.6	2.5–66	8.4–42.7	18.7–123.8
Loosmore–Skinner [24]	202	3.2–130.9	0.1–0.7	0.6–2.4	6.3–150	3.0–25.0	6.7–44.8
Ornatskii–Vinyarskii [25]	125	6.7–155.6	1.1–3.2	0.4–2.0	11.2–56	10.0–90.0	27.9–227.9
Ornatskii–Kichigan [26]	117	2.7–204.5	1.0–2.5	2.0	56	5.0–30.0	6.4–66.6
Ornatskii [27]	68	1.5–153.7	1.0–3.2	0.5	14	20.0–90.0	41.9–224.5
Knoebel *et al.* [28]	376	0.3–104.8	0.2–0.7	9.5	610	3.9–13.7	3.3–11.4
Mirshak *et al.* [29]	56	5.9–68.7	0.2–0.6	6.0–11.9	489–610	4.7–12.2	3.9–10.0
Babcock [30]	57	19.9–242.7	0.4–8.4	7.9–25.4	610	2.4–11.4	4.9–11.8
Burck–Hufschmidt [31]	143	16.7–60.8	1.1–3.1	10.0	350	0.9–3.8	4.5–12.2
Mayersak *et al.* [32]	1	18.0	2.9	11.7	585	44.4	42.8
Schaefer–Jack [33]	2	15.6–18.9	1.3–1.5	3.05	19	61.2–61.7	125.0–130.0
Thorgerson [34]	42	1.1–79.2	0.45	7.8–8.4	610	4.2–13.4	4.2–12.4
Zeigarnik *et al.* [35]	21	0.6–134.1	0.5–3.0	4.0	250	4.8–20.6	9.4–32.6
Gambill *et al.* [36]	23	8.8–23.9	0.1–0.5	3.2–7.8	37–416	7.0–53.0	7.0–48.7
Total	1865	0.3–242.7	0.1–8.4	0.3–25.4	2.5–610	0.9–90.0	3.3–227.9

recommended in the ranges $0.6 < G < 11$ Mg m^{-2} s^{-1}; $0.4 < p < 20.0$ MPa; $2 < D < 12$ mm.

Westinghouse [6]:

$$q''_{CHF} = (0.23\times10^6+0.094G)(3+0.01\Delta T_{sub})$$
$$\times[0.435+1.23\exp(-0.0093L/D)]^*$$
$$\times\left\{1.7-1.4\exp\left[-0.532\left(\frac{h_{sat}-h_{in}}{\lambda}\right)^{3/4}\left(\frac{\rho_g}{\rho_f}\right)^{-1/3}\right]\right\} \quad (2)$$

recommended in the ranges $0.3 < G < 11$ Mg m^{-2} s^{-1}, $5.7 < p < 20.0$ MPa, $1.25 < q''_{CHF} < 12.5$ MW m^{-2}, $0 < \Delta T_{sub} < 126$ K.

Tong [7]:

$$\frac{q''_{CHF}}{\lambda} = C\frac{G^{0.4}\mu_f^{0.6}}{D^{0.6}} \quad (3)$$

$$C = 1.76-7.433x_{ex}+12.222x_{ex}^2 \quad (4)$$

where λ is the latent heat and μ_f is the dynamic vis-

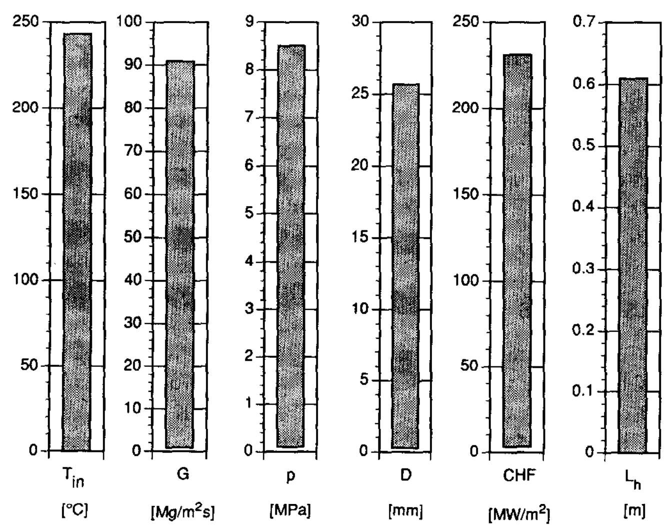

FIG. 1. Ranges of operating conditions for the data used in present calculations.

cosity of saturated liquid (SI units). The Tong correlation may be also presented in the form:

$$Bo = \frac{C}{Re^{0.6}} \quad (5)$$

where Bo and Re are Boiling number and Reynolds number, respectively. This correlation is often known as Tong-68 correlation. We modified the parameter C, together with a slight modification of the Reynolds number power, to give a more accurate prediction in the range of pressures below 5.0 MPa, as the Tong correlation was recommended for pressures higher than 7.0 MPa. The modification of the Tong correlation was based on data reported in refs. [18]–[21] ($2.2 < G < 40$ Mg m^{-2} s^{-1}, $0.1 < p < 5.0$ MPa, $2.5 < D < 8.0$ mm, $12 < L/D < 40$, $15 < \Delta T_{sub,ex} < 190$ K, $4.0 < q''_{CHF} < 60.6$ MW m^{-2}). The new expression of the Tong correlation is

$$Bo = \frac{C}{Re^{0.5}} \quad (6)$$

with

$C = (0.216 + 4.74 \times 10^{-2} p)\Psi$ [p in MPa]
$\Psi = 0.825 + 0.986 x_{ex}$ if $x_{ex} > -0.1$;
$\Psi = 1$ if $x_{ex} < -0.1$
$\Psi = 1/(2 + 30 x_{ex})$ if $x_{ex} > 0$
(exit saturated conditions).

Tong-75 [8]:

$$q''_{CHF} = 0.23 f_0 G \lambda \left[1 + 0.00216 \left(\frac{p_{ex}}{p_{crit}} \right)^{1.8} Re^{0.5} Ja \right] \quad (7)$$

where

$$f_0 = \frac{8\left(\frac{D_e}{D_0}\right)^{0.32}}{Re^{0.6}}$$

with $D_0 = 1.27 \times 10^{-2}$ m

$$Re = \frac{GD}{\mu_f(1-\alpha)}$$

with α evaluated by using Thom's correlation [42];

$$Ja = \frac{C_p(T_b - T_{sub})}{\lambda} \frac{\rho_f}{\rho_g}$$

recommended in the ranges $7.0 < p < 14.0$ MPa, $3 < D < 10$ mm, $5 < L/D < 100$, $0.7 < G < 6.0$ Mg m^{-2} s^{-1}, $-1.0 < x_{in} < 0.0$.

AVAILABLE MODELS

As is known, models have the advantage, with respect to correlations, of being able to characterize not only the existing and developing data base, but also to be used to predict CHF beyond the established data base. In this sense visual information, not available so far in detail, would be of great help for a full understanding of the basic mechanisms of CHF in subcooled flow boiling at high liquid velocity and inlet subcooling, enabling the development of a mechanistic model of CHF more closely to reality. Anyway, at the moment, three different models are available in the literature for the prediction of the CHF in subcooled flow boiling: the Weisman and Ileslamlou [9], the Lee and Mudawar [10] and the Katto [11] models. The Weisman and Ileslamlou model [9] (extension of the Weisman and Pei model [43]) is based on the existence of a bubbly layer adjacent to the heater surface. At the CHF, the bubbles agglomerate into a vapour blanket that prevents the liquid core from cooling the heater wall. It assumes that the turbulent interchange at the outer edge of the bubbly layer is the limiting mechanism. The void fraction in the bubbly layer is determined by a balance between the outward vapour flow away from the wall and the inward liquid flow at the bubbly layer-core interface. They postulated that CHF occurs when the void fraction in the bubbly layer just exceeds the critical value of 0.82. The void fraction was calculated under the assumption of homogeneous two-phase flow in the bubbly layer. With reference to the previous model description the new one accounts for high subcooling condition effects (energy balance at the bubbly layer-core interface) making the computation of the CHF an entirely local calculation (authors claim that under subcooled and low quality conditions CHF is a local phenomenon). Authors tested and assessed their model within the following parameters ranges: $-0.12 \geq x_{ex} \geq -0.46$; $p = 6.8$–19 MPa; $D = 1.9$–37.5 mm; $L = 76$–1950 mm; $G = 1.3$–10.5 Mg m^{-2} s^{-1}.

The Lee and Mudawar model [10] (liquid sublayer dryout model) is a mechanistic CHF model based on the observation that, during fully developed boiling, a vapour blanket forms in the vicinity of the heated wall by the coalescence of small bubbles, leaving a thin liquid sublayer in contact with the heated wall beneath the blanket. The onset of sublayer dryout was assumed to be triggered by a Helmholtz instability at the sublayer–vapour blanket interface, and CHF was postulated to occur when the rate of heat supplied at the wall exceeds the enthalpy of fresh liquid entering the sublayer from the bubbly layer and core regions (or, in other terms, when the rate of sublayer mass loss by evaporation exceeds that of the liquid entering the sublayer from the core region). Although the model is mechanistic in nature, describing a specific process associated with CHF, its development requires the use of available correlations to describe the dynamics of bubbles in the wall region. The model was assessed by the authors (choice of correlations) on the following ranges of parameters: $p = 5$–17.6 MPa; $G = 1$–5.2 Mg m^{-2} s^{-1}; $D = 4$–16 mm; $\Delta T_{sub} = 0$–59 K. The two models reported above were proposed by respective authors for high pressure conditions. In particular, the Lee and Mudawar model was developed for high pressure conditions only since it assumes the existence of a vapour layer in a small wall region while maintaining a velocity profile in the core liquid which can be represented by the law of the wall. This condition is simply not valid for low pressure systems and the model is, therefore, not expected to yield accurate CHF predictions at low pressure. Similar premises could be forwarded for the Weisman and Ileslamlou model. As already stated in the introduction, they are applied here for low pressure conditions just to check their performances in this operating ranges. In particular, the Lee and Mudawar model looks very attractive for its mechanistic nature and can be considered as a starting point to obtain a model whose validity could be extended to low pressure conditions.

The Katto model [11] is based on the same mechanism as the Lee and Mudawar model, from which it borrows much of the original derivation, i.e. liquid sublayer dryout mechanism. A thin vapour layer or slug (called 'vapour blanket') is formed, due to accumulation and condensation of the vapour furnished from the wall, overlying a very thin liquid sublayer adjacent to the wall. CHF is assumed to occur when the liquid sublayer is extinguished by evaporation during the passage time of the vapour blanket sliding on it. Parameters to be determined in the description of the mechanistic model by Katto are: initial thickness of the sublayer, δ, vapour blanket length, L_B, and velocity, U_B. The evaluation of δ is obtained differently from Lee and Mudawar model using a non-dimensional correlation derived in a previous study of CHF in pool boiling [44]. Vapour blanket length L_B is set equal to the critical wavelength of Helmholtz instability of the liquid–vapour interface (same as in the Lee and Mudawar model). Vapour blanket velocity U_B is evaluated by relating it to the local velocity U_δ of the near wall two-phase flow (which is assumed to be homogeneous flow) at a distance δ from the tube wall. U_δ is evaluated by the Karman velocity distribution and U_B is set equal to kU_δ, where k is called the velocity coefficient and is the only one quantity to be determined empirically in the Katto model. The velocity coefficient k (non-dimensional correlation as a function of Reynolds number, liquid and vapour density, and void fraction) was derived on data-sets published in refs. [12, 15, 18, 45–46], practically transforming the model in an empirical correlation. The Katto model results tested on the following range of parameters (water): $D = 1.14$–11.07 mm; $p = 0.1$–19.6 MPa; $G = 0.35$–40.6 Mg m^{-2} s^{-1}; $\Delta T_{sub,out} = 0$–117.5 K.

RESULTS

A summary of present calculations is reported in Tables 2–4, where the performances of correlations and models used are given. Table 2 reports the performances of correlations and models in terms of maximum deviation from the experimental value, i.e. the percentage of data points predicted within a given error band. A graphic representation of these results is shown in Fig. 2, where the percentage of data points predicted within a given error band is plotted against the error band. The best statistics are provided by the modified-Tong correlation and Katto models that both predict the CHF accurate to 25% for about 75% of the time (76.5% for modified-Tong correlation and 72.3% for Katto model). They show a very similar behaviour, even though the modified-Tong correlation almost always exhibits a higher percentage of points predicted within the fixed error band. It must be pointed out that the Katto model, contrarily to all other correlations and models, is not able to calculate all the data points. It fails for 950 points out of 1865 (50.9%) that are discarded for the reason that the calculation procedure of the Katto model requires a void fraction in the boiling layer less than 0.7. This condition is matched whenever the inlet subcooling is medium/low and is associated with low velocity or low mass flow rate. This is the limit considered by the author for the validity of the assumption of homogeneous flow in the two-phase boundary layer. For conditions where a higher void fraction is predicted in the calculation procedure the model fails the evaluation of the CHF. Among the other three correlations (Levy, Westinghouse and Tong-75) Westinghouse correlation provides a fairly good prediction, even though below the performance of modified-Tong correlation. Tables 3 and 4 report the r.m.s. error for correlations and models, respectively, and for each data-set analyzed, besides the total values. A graphic representation of these results is shown in Fig. 3, where the r.m.s. error is plotted vs the different data-sets employed. Globally the best behaviour is exhi-

Table 2. Performance of correlations and models in term of maximum deviation from the experimental value

Correlation model	% of points within ±15%	% of point within ±25%	% of points within ±30%	% of points within ±50%	Calculated points
Katto	51.8	72.3	80.1	95.7	915
Lee–Mudawar	3.14	6.5	8.8	20.1	1847
Weisman–Ileslamlou	17.8	30.9	37.1	59.9	1864
Tong-75	30.2	47.3	52.9	65.8	1865
Westinghouse	40.1	65.4	74.8	93.8	1865
Levy	22.8	37.7	43.5	61.3	1859
mod.-Tong	55.0	76.5	82.7	98.1	1865

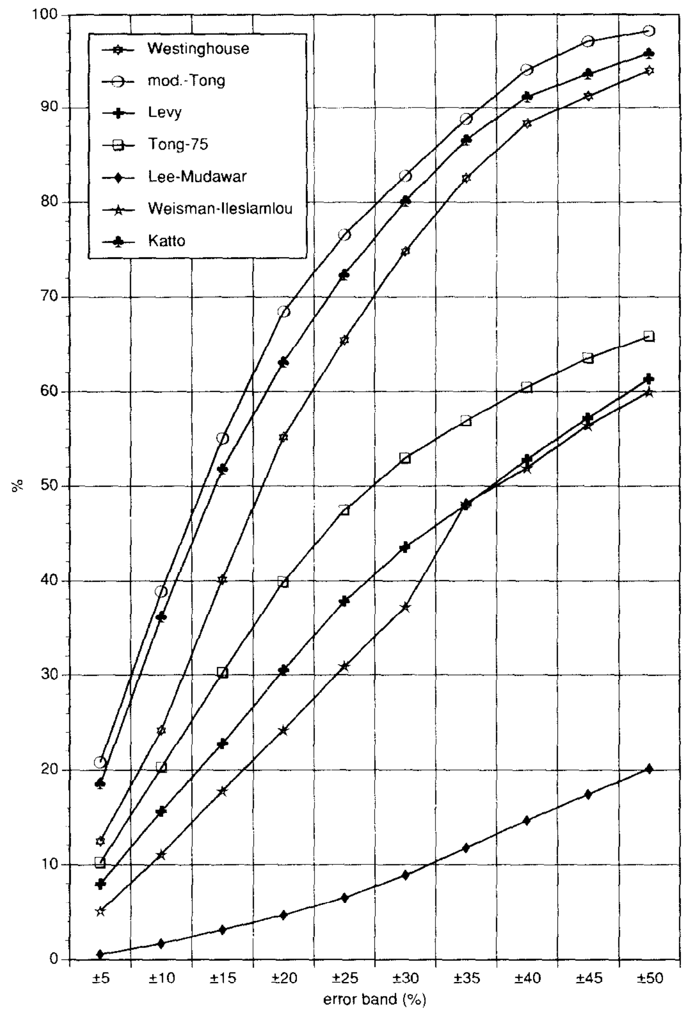

FIG. 2. Percentage of data points predicted within a given error band vs the error band.

bited by the modified-Tong correlation that shows a global r.m.s. error of 21.2%. A slightly higher global r.m.s. error, 24.5%, is given by the Katto model, that provides the best prediction among models (with the limitations on the total number of calculated points as above). From Fig. 3 and Tables 3 and 4 it is also possible to observe the behaviour of used correlations and models for each different reference data-set. Modified-Tong correlation shows a better r.m.s. error than Katto model for seventeen data-sets out of twenty-four.

Apart from the pure statistics, that may be of some help to establish the merits of predictive tools but are certainly not exhaustive for a comprehensive analysis of them, results of calculated vs experimental CHF values are plotted in Fig. 4 for the four correlations and in Fig. 5 for the three models. Figures 6–12 report, for each correlation and model, the ratio bewcen calculated and experimental CHF vs the main thermal-hydraulics and geometric parameters, i.e. mass flux, pressure, channel diameter and channel length. Among the correlations, as expected by the above statistics, the most homogeneous behaviour is provided by the modified-Tong correlation that, although assessed on ENEA data [18–21], is able to give a good prediction of all the other data-sets. Only a few data from Ornatskii *et al.* [25–27] in the range 40–75 MW m^{-2} are overpredicted above the average value (small diameters). The Westinghouse and the Levy correlations give an underprediction of Nariai *et al.* data [16] (atmospheric pressure and very small tube diameters) and Vandervort *et al.* data [23] (very small tube diameters). The Westinghouse correlation also overpredicts the Gambill–Greene data [22] (atmospheric pressure), while the Levy correlation overpredicts most of Boyd data [12–14] and underpredicts the very high CHF data of Ornatskii *et al.* [25–27]. The Tong-75 correlation essentially fails in the prediction of Gambill–Greene, and Nariai *et al.* data-sets, both at atmospheric pressure, and Ornatskii *et al.* data sets. For the data-sets not mentioned, all the three correlations are able to predict most of the data

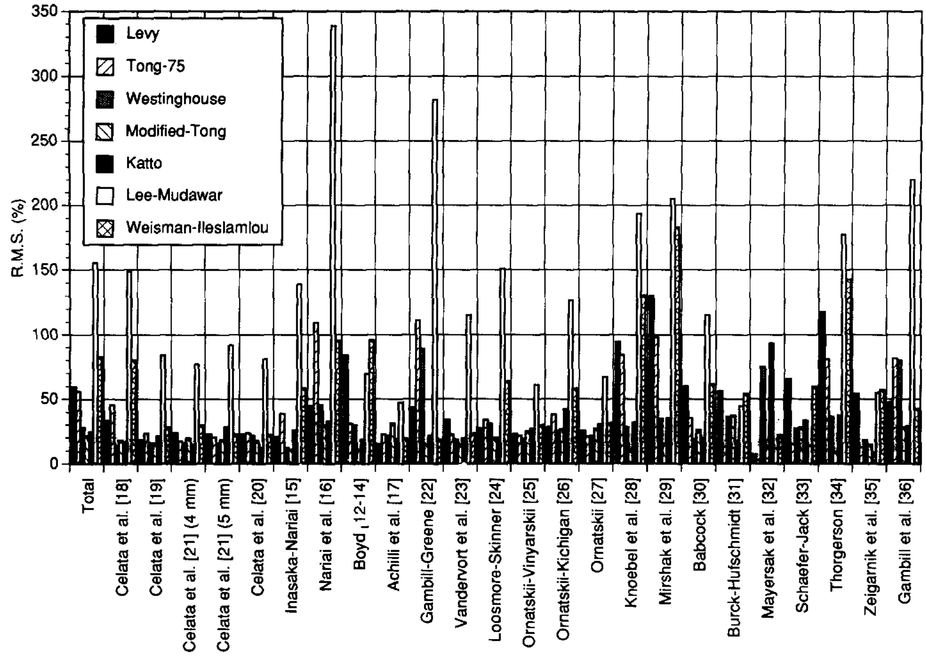

FIG. 3. Calculated r.m.s. errors vs data-sets.

within ±25%. Being developed for LWR conditions, the above correlations were proposed for tube diameters above 2–3 mm and pressures higher than 4.0–5.0 MPa. Their failure was therefore expected when predicting experimental data characterized by very low pressure and/or very small tube diameter. It is instead surprising that the mass flux, considerably higher than the upper limit recommended for the above correlations (11 Mg m^{-2} s^{-1}), does not show, globally, a dramatic systematic effect such as the pres-

Table 3. Calculated r.m.s. errors for the correlations

Correlation CHF Data [ref.]	Levy r.m.s. [%]	Levy Points	Tong-75 r.m.s. [%]	Tong-75 Points	Westinghouse r.m.s. [%]	Westinghouse Points	mod.-Tong r.m.s. [%]	mod.-Tong Points
Total	59.5	1859	55.6	1865	27.7	1865	21.2	1865
Celata *et al.* [18]	33.0	43	45.4	43	13.6	41	18.0	43
Celata *et al.* [19]	17.9	88	22.9	44	15.2	88	15.5	88
Celata *et al.* [21]	23.3	48	16.8	48	15.6	48	19.3	48
Celata *et al.* [21]	22.3	7	20.2	7	15.1	7	18.0	7
Celata *et al.* [20]	22.5	60	23.1	60	21.1	60	17.4	60
Inasaka-Nariai [15]	20.4	29	38.3	29	12.1	29	10.6	29
Nariai *et al.* [16]	44.6	95	109.1	95	45.3	95	29.0	95
Boyd [12–14]	84.0	8	30.3	10	29.3	10	10.9	10
Achilli *et al.* [17]	14.8	35	22.2	35	21.2	35	30.7	35
Gambill–Greene [22]	43.4	7	111.2	7	89.0	7	14.4	7
Vandervort *et al.* [23]	33.5	210	22.2	210	18.3	210	14.6	210
Loosmore–Skinner [24]	27.0	202	33.4	202	30.6	202	19.6	20
Ornatskii–Vinyarskii [25]	22.7	125	21.3	125	18.5	125	24.8	125
Ornatskii–Kichigan [26]	27.9	117	37.9	117	25.1	117	26.1	117
Ornatskii [27]	24.9	68	20.8	68	21.0	68	26.8	68
Knoebel *et al.* [28]	94.3	376	84.0	376	27.6	376	10.8	376
Mirshak *et al.* [29]	130.0	52	98.3	56	34.7	56	15.2	56
Babcock [30]	59.9	57	34.9	57	18.6	57	25.8	57
Burck–Hufschmidt [31]	56.1	143	13.0	143	36.1	143	37.2	143
Mayersak *et al.* [32]	7.1	1	2.6	1	74.9	1	13.4	1
Schaefer–Jack [33]	65.6	2	14.9	2	26.8	2	27.8	2
Thorgerson [34]	117.5	42	80.7	42	36.3	42	8.9	42
Zeigarnik *et al.* [35]	54.3	21	12.3	21	17.8	21	14.5	21
Gambill *et al.* [36]	47.7	23	81.5	23	80.1	23	27.6	23

Table 4. Calculated r.m.s. errors for the models

Model CHF Data [ref.]	Katto r.m.s. [%]	Katto Points	Lee–Mudawar r.m.s. [%]	Lee–Mudawar Points	Weisman–Ileslamlou r.m.s. [%]	Weisman–Ileslamlou Points
Total	24.5	915	155.1	1847	82.6	1864
Celata *et al.* [18]	16.8	26	148.6	43	80.3	43
Celata *et al.* [19]	21.2	81	83.9	88	27.5	88
Celata *et al.* [21]	14.6	42	76.8	48	29.1	48
Celata *et al.* [21]	27.8	5	91.5	7	22.4	7
Celata *et al.* [20]	11.9	58	80.6	60	22.0	60
Inasaka–Nariai [15]	25.5	15	138.8	29	58.2	29
Nariai *et al.* [16]	32.4	17	338.3	95	95.3	95
Boyd [12–14]	18.0	6	69.3	10	95.5	10
Achilli *et al.* [17]	19.1	35	47.4	35	18.9	35
Gambill–Greene [22]	21.0	7	282.0	7	18.2	7
Vandervort *et al.* [23]	19.2	155	115.2	210	23.0	210
Loosmore–Skinner [24]	19.7	12	151.2	202	63.7	202
Ornatskii–Vinyarskii [25]	26.9	121	61.0	125	29.5	125
Ornatskii–Kichigan [26]	42.1	31	126.9	117	58.2	117
Ornatskii [27]	30.0	61	67.2	68	31.0	68
Knoebel *et al.* [28]	31.4	107	193.6	376	130.2	375
Mirshak *et al.* [29]	35.3	6	205.2	56	182.9	56
Babcock [30]	19.2	32	115.6	57	61.8	57
Burck–Hufschmidt [31]	17.3	57	44.4	125	54.5	143
Mayersak *et al.* [32]	93.2	1	11.6	1	21.9	1
Schaefer–Jack [33]	32.9	2	13.7	2	60.0	2
Thorgerson [34]	37.5	8	177.7	42	142.7	42
Zeigarnik *et al.* [35]	8.58	11	55.0	21	57.3	21
Gambill *et al.* [36]	28.7	23	220.0	23	42.8	23

sure or the tube diameter or length. A substantial absence of systematic deviations is presented by the modified-Tong correlation.

As far as model predictions are concenred, the Katto model turns out to be the best one in the present calculations, with an even distribution of points within the error band. The model was assessed only on data [12, 15, 18] among those used in present calculations and works very well with the other data-sets. A small systematic effect (underprediction) is shown by the channel length (Fig. 12) for very short channel data. It must be considered, however, that the Katto model is unable to give a prediction for about one half of the available experimental data, as stated above. This is, unfortunately, a limiting aspect of this interesting predicting tool. The Weisman and Ileslamlou model provides predictions affected by a systematic error, even though, globally, some of them lie within $\pm 25\%$. The Lee and Mudawar model gives a general inadequacy in the prediction of available low pressure data. As expected, both the Weisman and Ileslamlou and the Lee and Mudawar models show a systematic dependence on thermal-hydraulic and geometric parameters (Figs. 10 and 11), even though the Lee and Mudawar model shows a successful prediction of high pressure data. It must be pointed out again that both these two models were assessed, and therefore recommended by respective authors, in their proposed version, in a range of pressure above 7.0 MPa, and then outside the pressure range of used data.

CONCLUDING REMARKS

With the aim of establishing the bounds of validity of existing predictive tools for the calculation of the CHF in subcooled flow boiling, four correlations (Levy, Westinghouse, modified-Tong and Tong-75) and three models (Weisman and Ileslamlou, Lee and Mudawar and Katto) have been statistically analysed using twenty-four data sets available in literature for a total of 1865 data points, in wide ranges of operating conditions typical of fusion reactor thermal-hydraulics requirements ($0.1 < p < 8.4$ MPa; $0.3 < D < 25.4$ mm; $0.1 < L < 0.61$ m; $2 < G < 90.0$ Mg m^{-2} s^{-1}; $90 < \Delta T_{sub,in} < 230$ K). Statistics and r.m.s. errors have been calculated for each predictive tool and each data-set, and comparisons of correlations and model predictions with experimental data have been shown. Correlations and models have been characterized in terms of thermal hydraulic (mass flux and pressure) and geometric (channel diameter and length) parameters to ascertain possible systematic effects in predictive tools performances.

Among the correlations, a very good agreement with experimental data is shown by the modified-Tong correlation (modified on the basis of ENEA data [18–21]) characterized by a very good statistics (76.5% of predictions are within $\pm 25\%$) and by an r.m.s. error of 21.2%. The wide ranges of operating conditions which the present calculations have been done on, allow us to give this correlation (which has the advantage of being a very simple correlation) a good

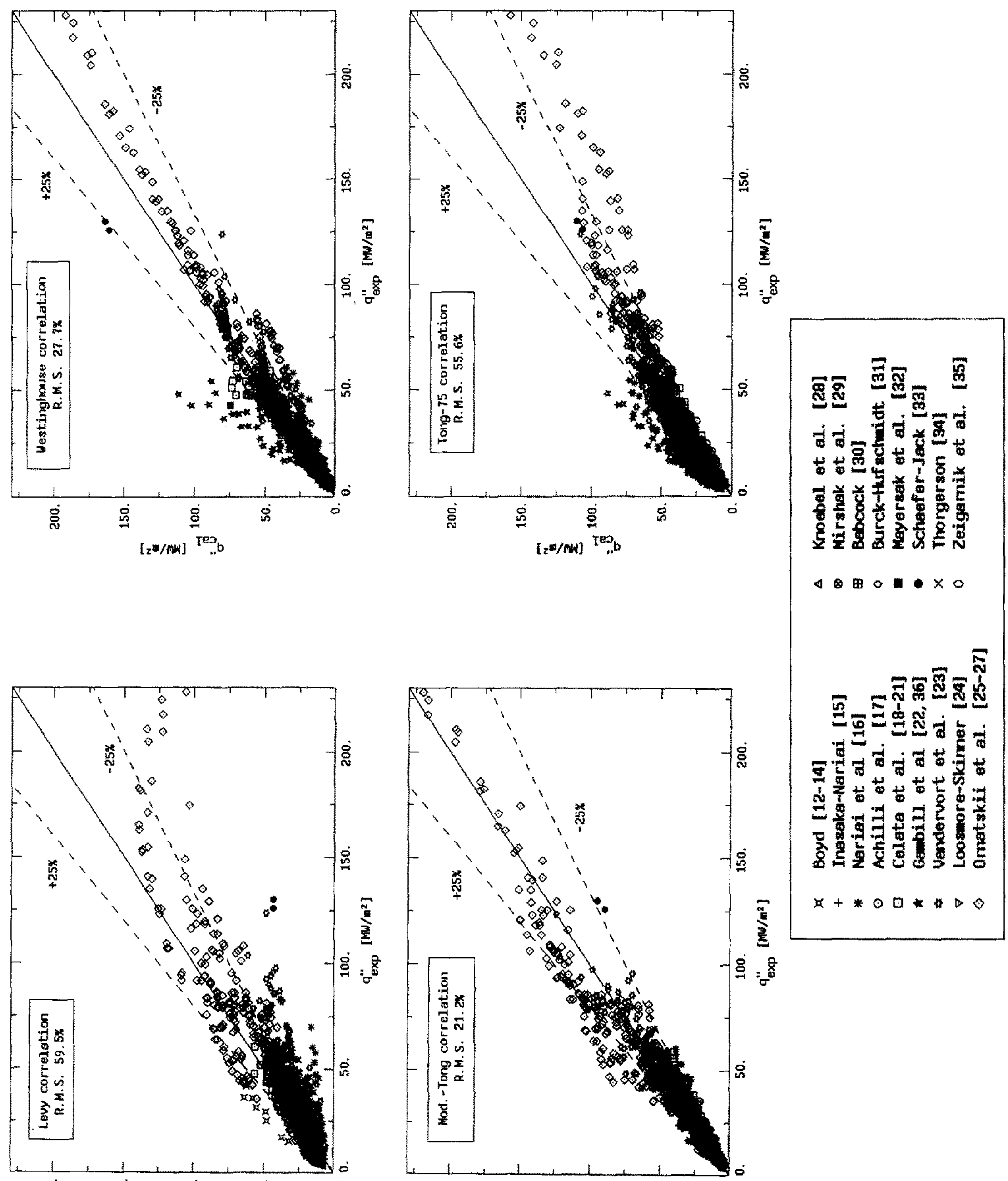

FIG. 4. Calculated vs experimental CHF for the four correlations.

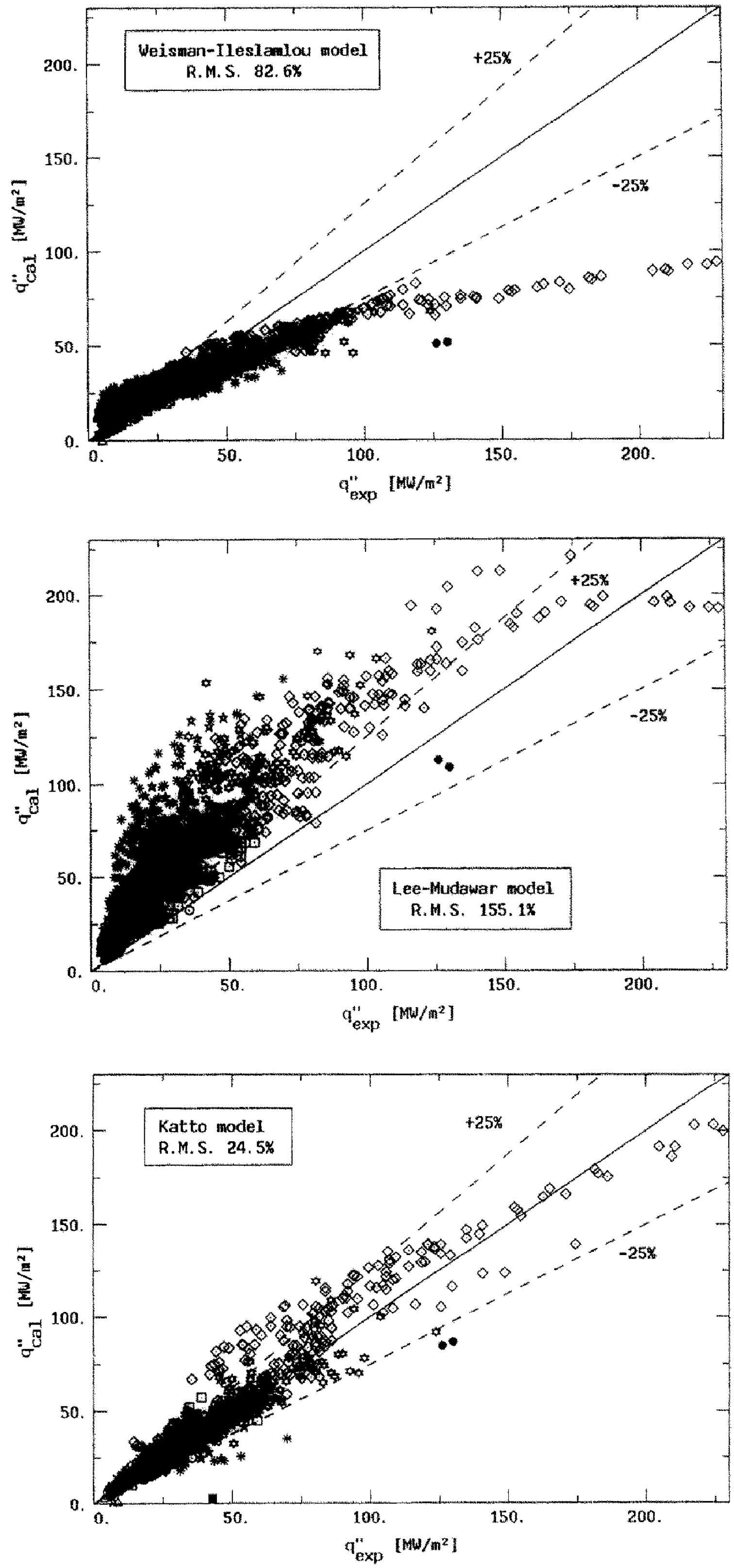

FIG. 5. Calculated vs experimental CHF for the three models. See Fig. 4 for legend.

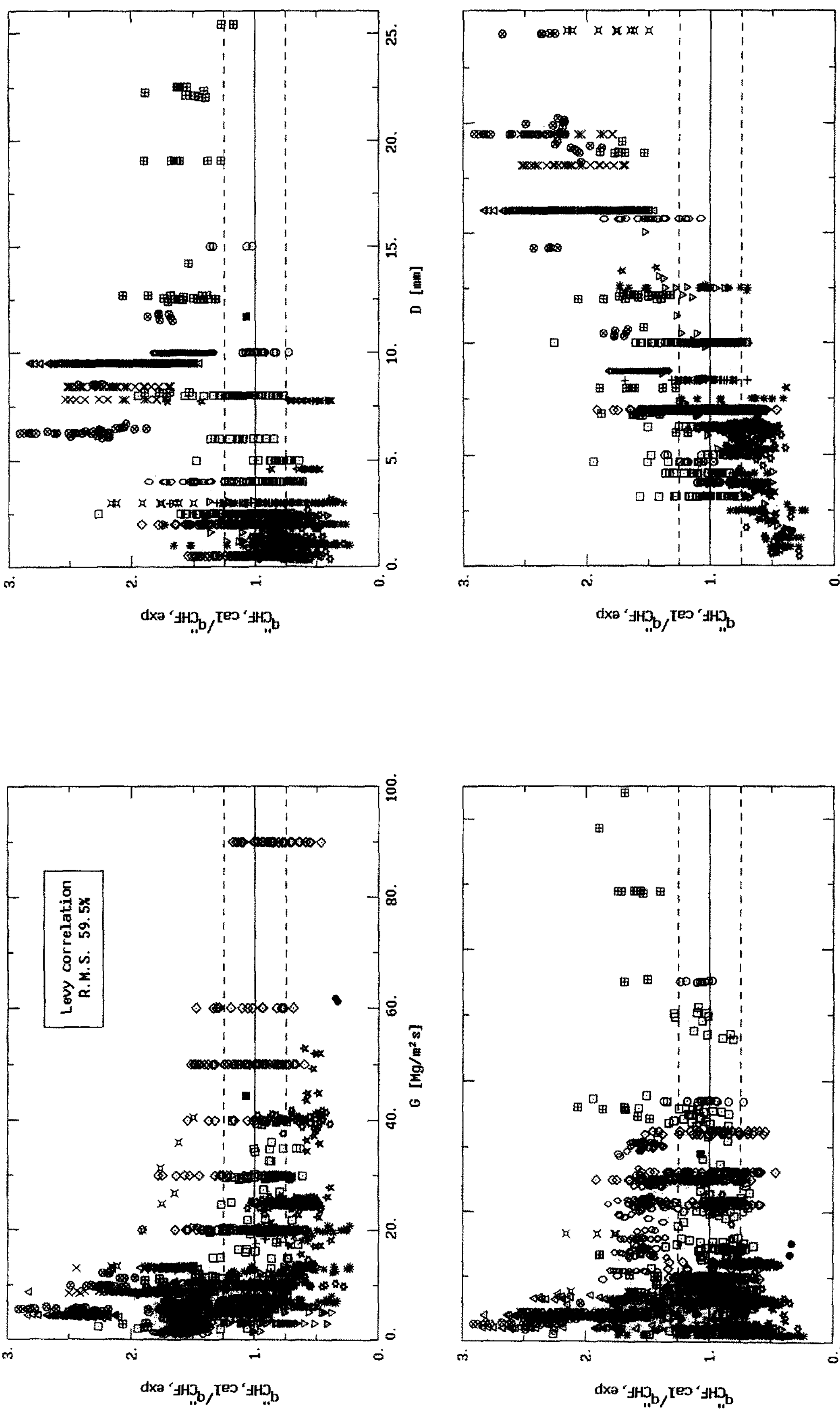

FIG. 6. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Levy correlation. See Fig. 4 for legend.

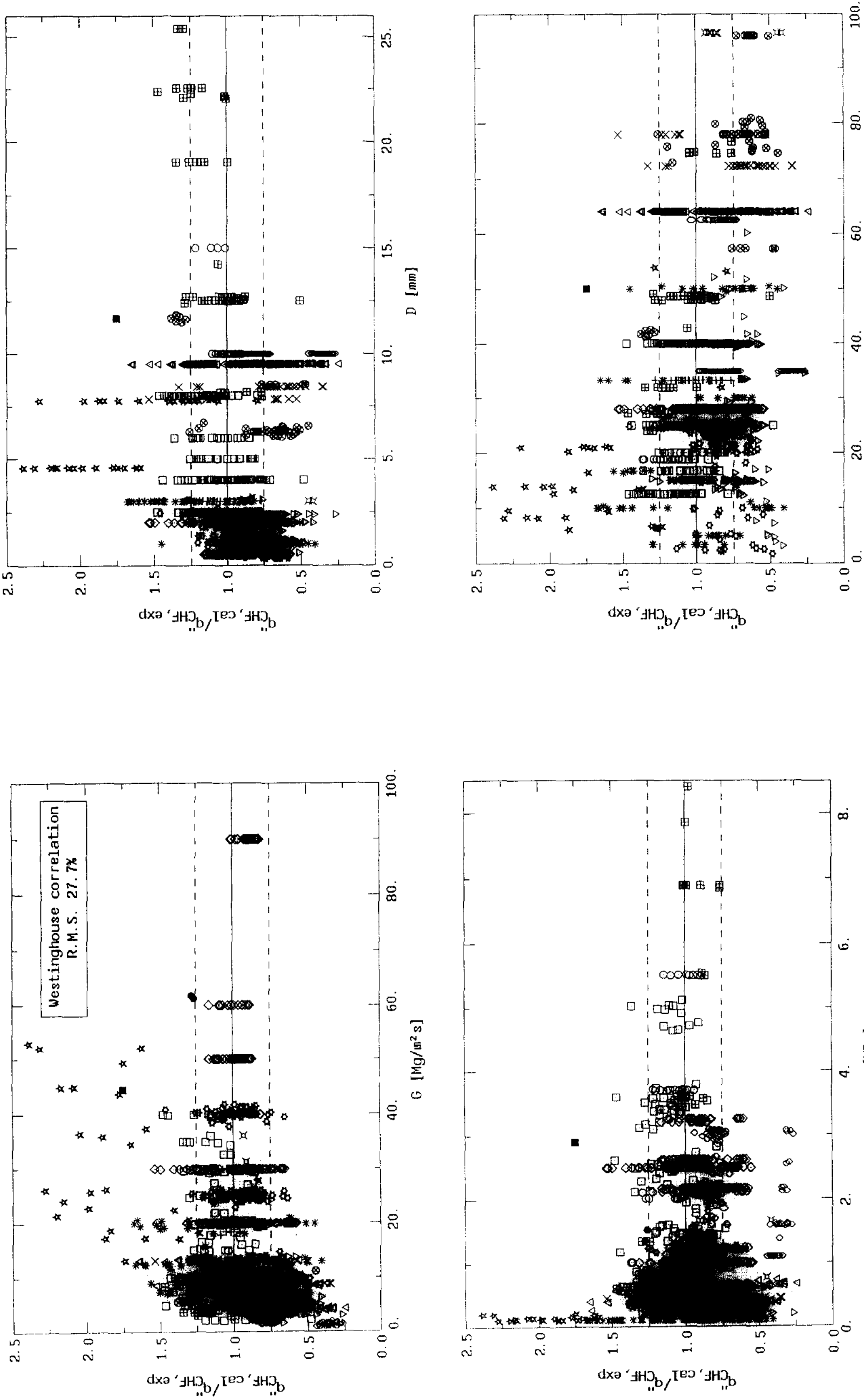

FIG. 7. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Westinghouse correlation. See Fig. 4 for legend.

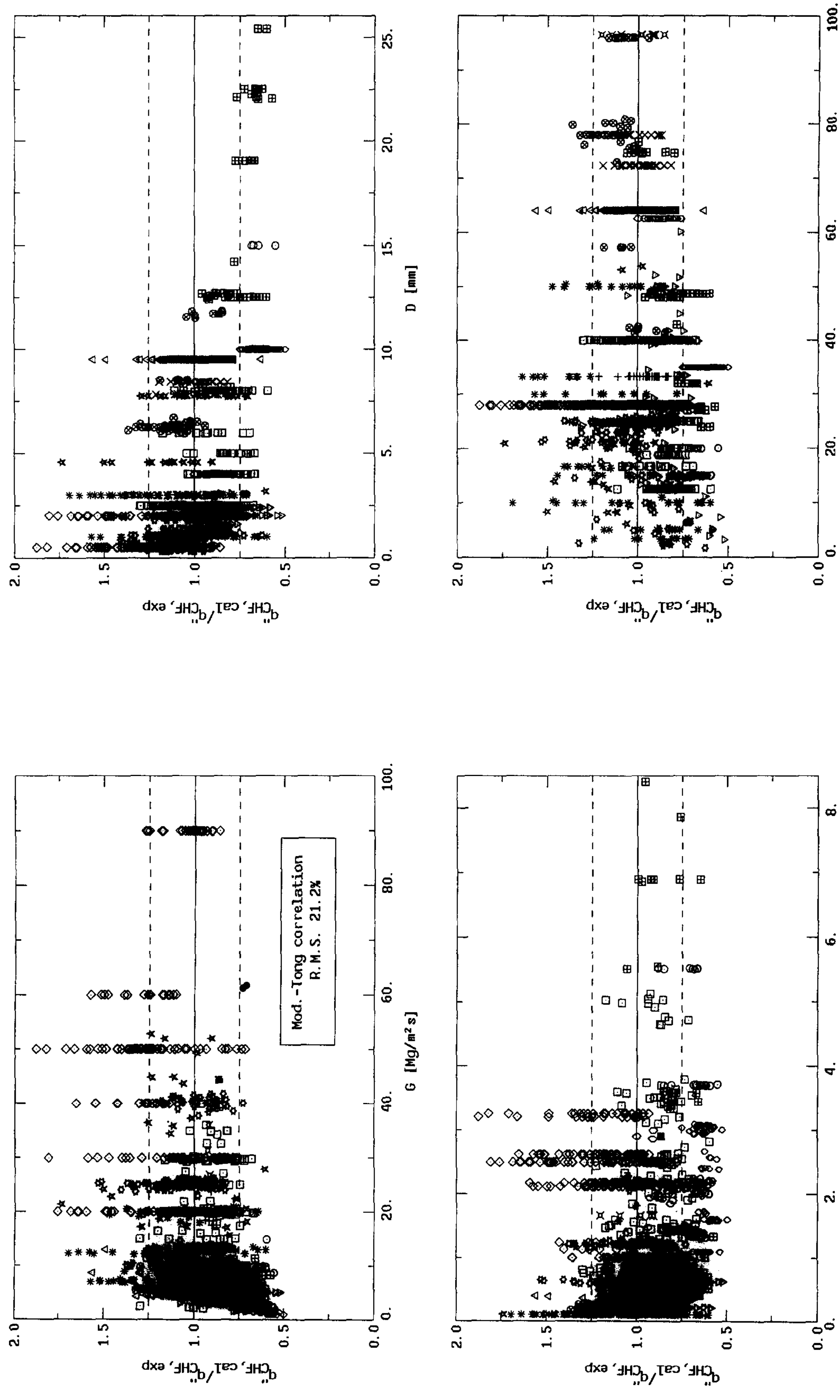

FIG. 8. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for modified-Tong correlation. See Fig. 4 for legend.

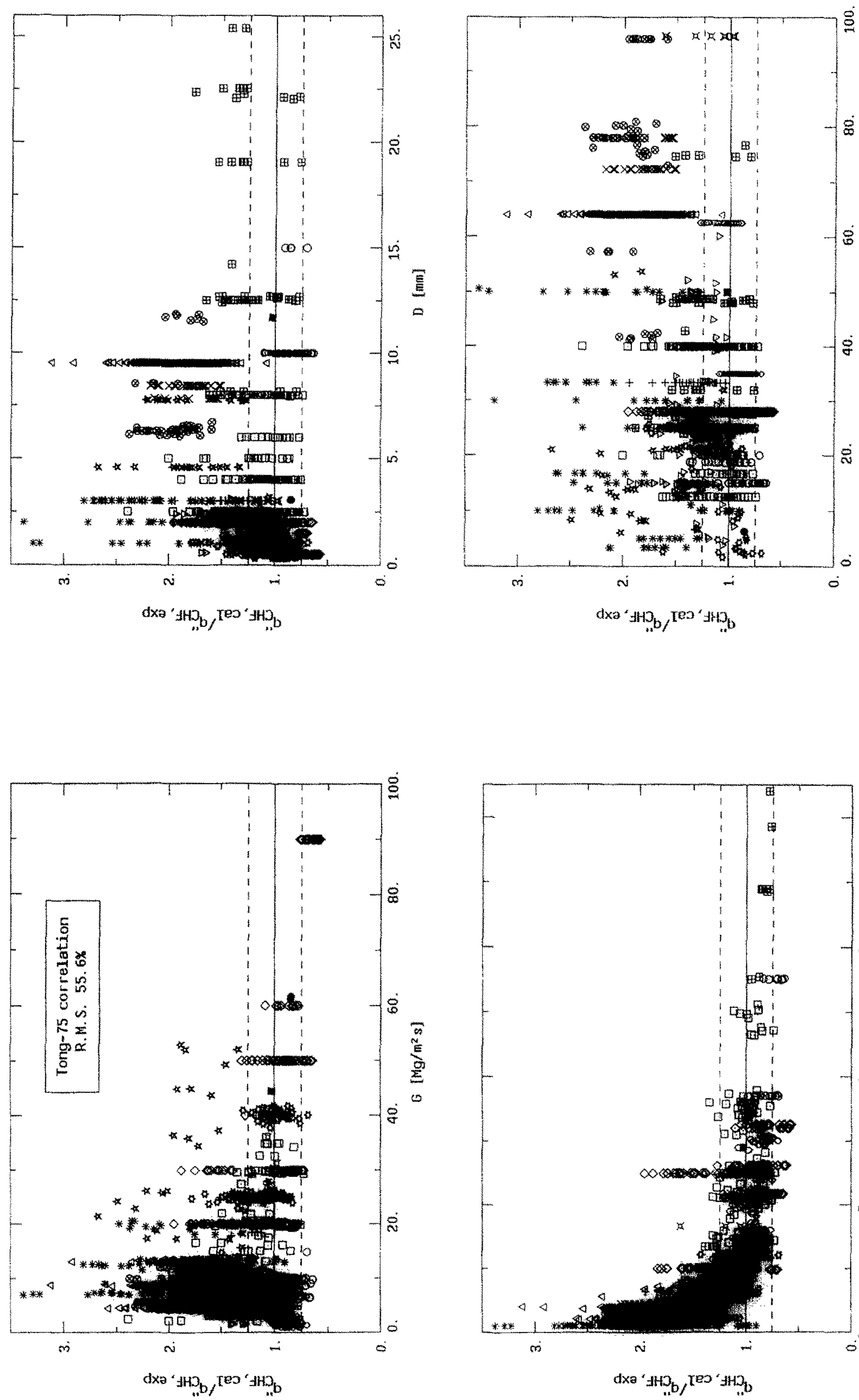

FIG. 9. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Tong-75 correlation. See Fig. 4 for legend.

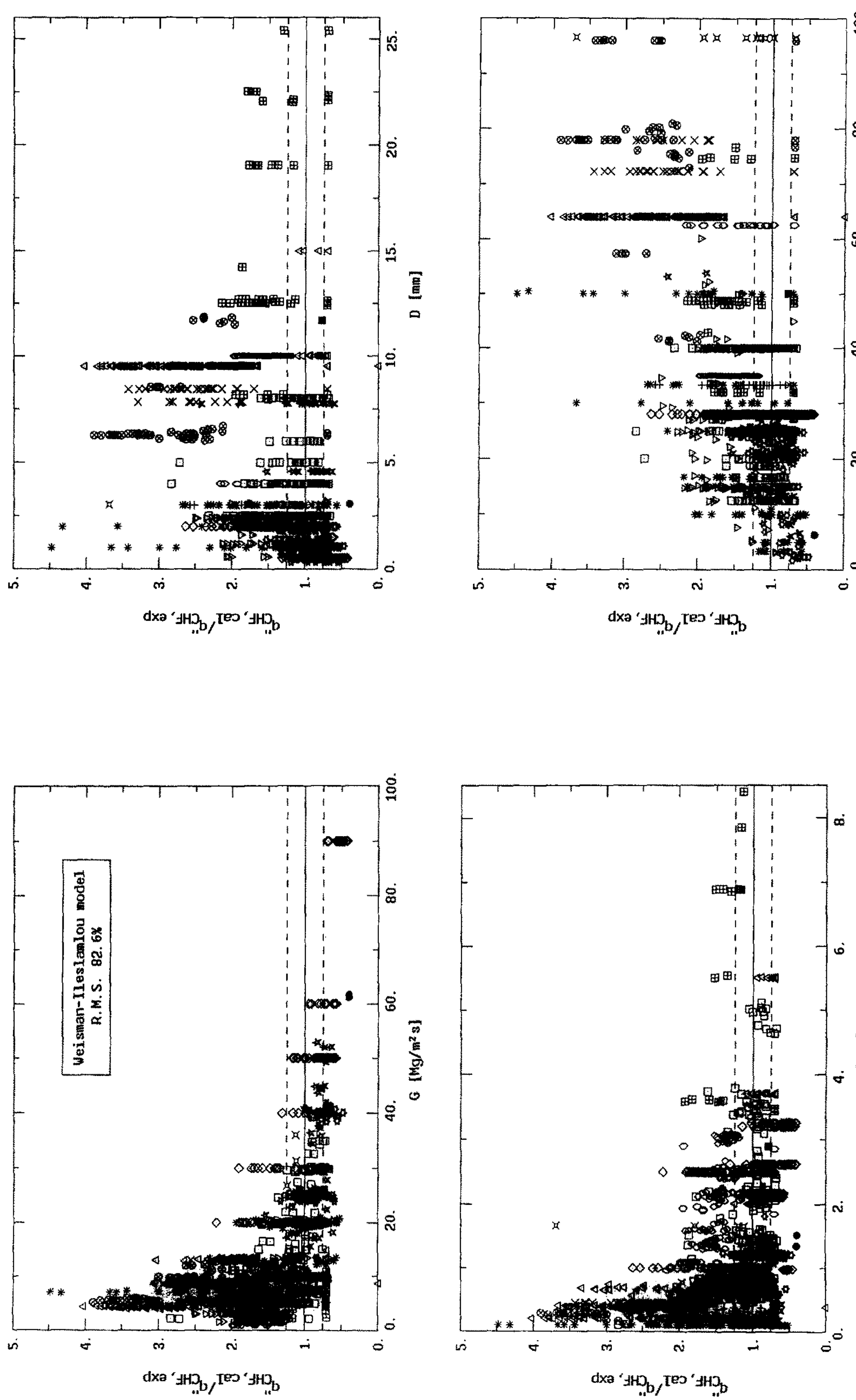

FIG. 10. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Weisman–Ileslamlou model. See Fig. 4 for legend.

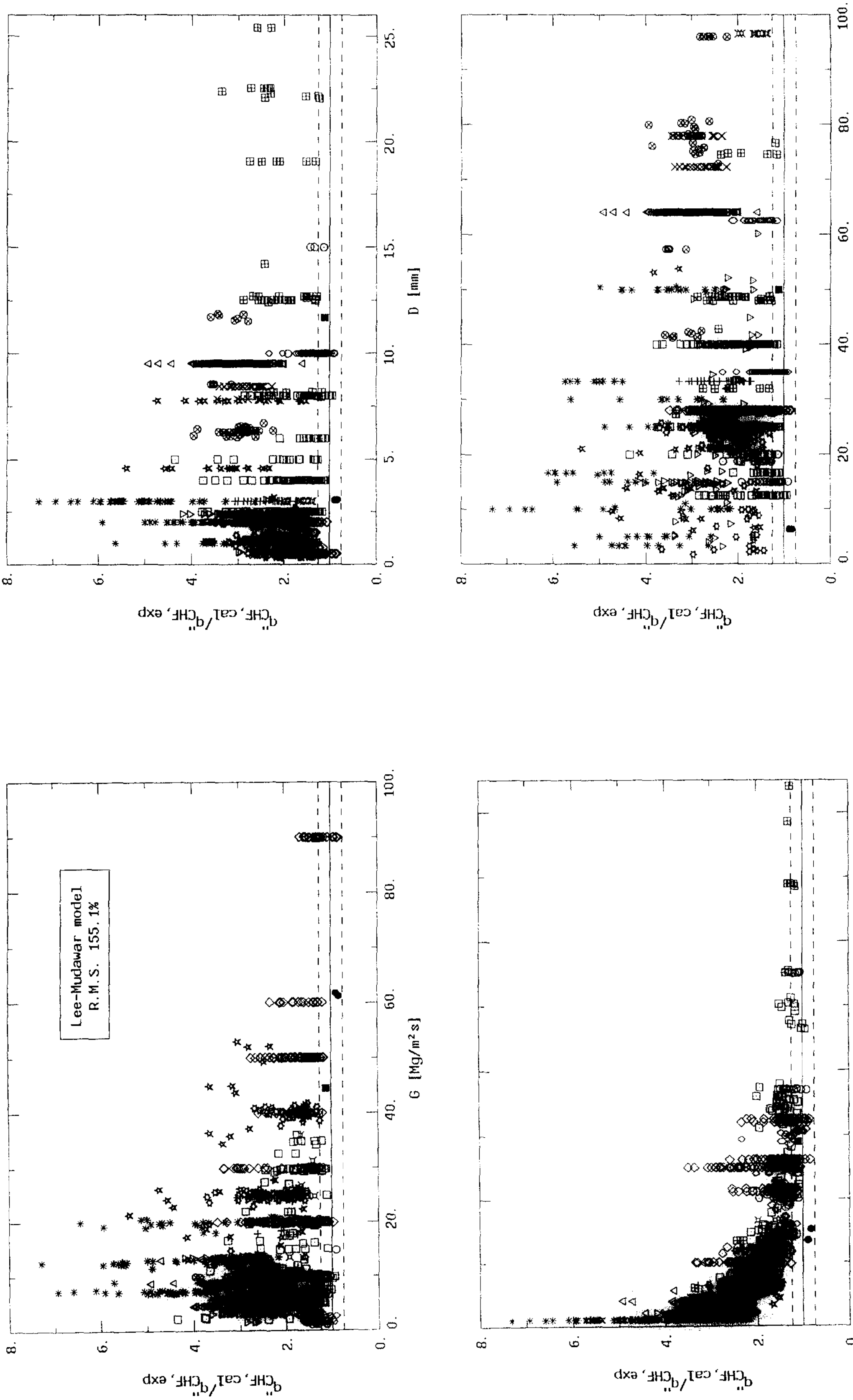

FIG. 11. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Lee–Mudawar model. See Fig. 4 for legend.

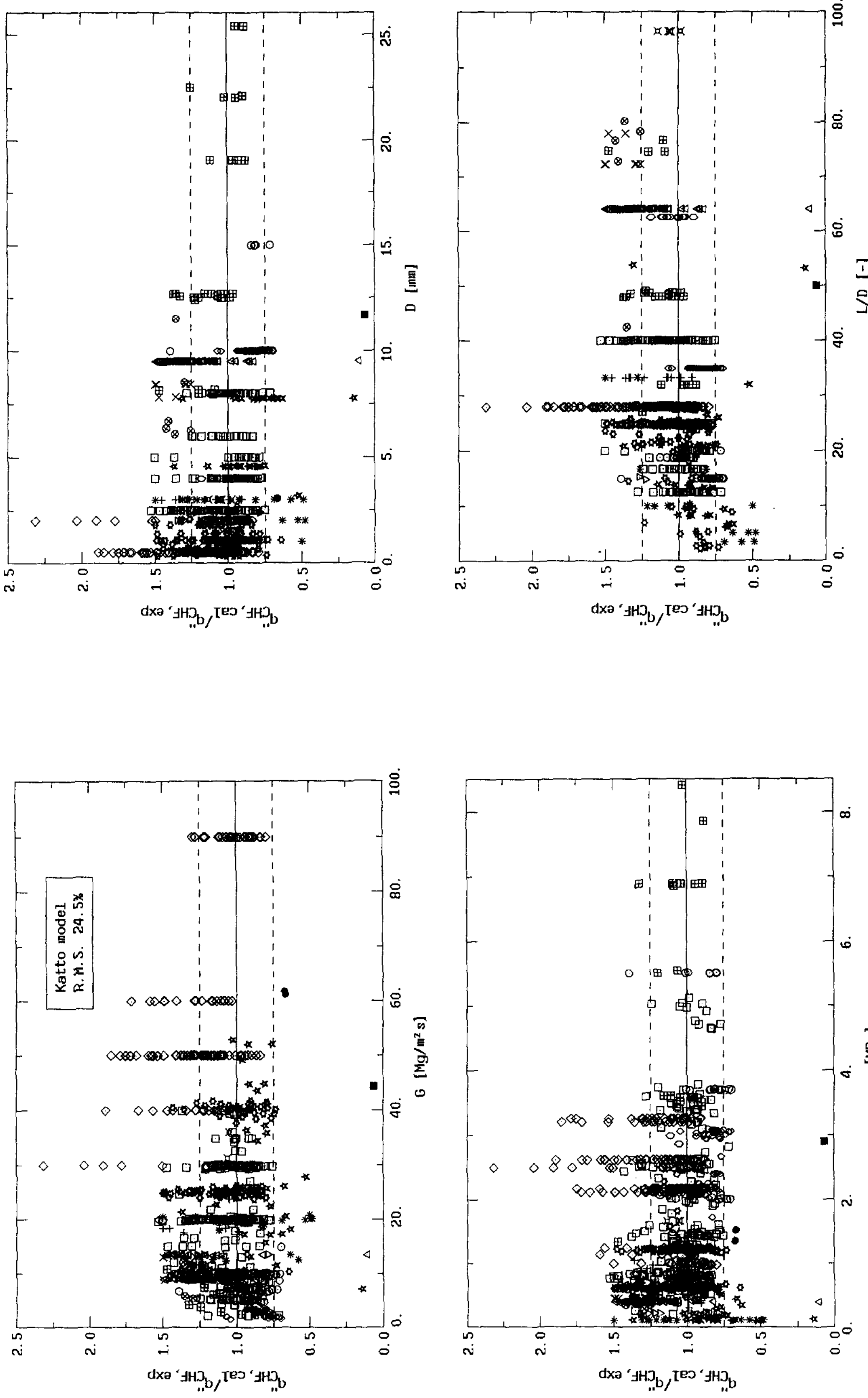

FIG. 12. Calculated-to-experimental CHF ratio vs mass flux, pressure, channel diameter and channel length for Katto model. See Fig. 4 for legend.

reliability for the prediction of the CHF in subcooled flow boiling. Other correlations show a fairly good agreement with many experimental data, but are unreliable when used very far from the recommended ranges of application.

Among the models, a very good prediction of experimental data is provided by the Katto model, which was proposed by the author on the basis of few present data ([12, 15, 18]). The model is characterized by good statistics (72.3% of predictions are within ±25%) and by a r.m.s. error of 24.5%. A limit of the Katto model is represented by the fact that it is not able to calculate all the data points. It fails for 950 points out of 1865 (50.9%) that are therefore discarded. This is due to the calculation procedure of the Katto model that requires a void fraction in the boiling layer less than 0.7. This is the limit considered by the author for the validity of the assumption of homogeneous flow in the two-phase boundary layer. The Katto model, although mechanistic in nature, shows the necessity, like the other two models, of empirical parameters introduced in the mathematical description of the dynamics of the bubbles that must be derived from experiments. It is therefore still necessary to accomplish a full understanding of the phenomenon to propose a realistic and pure mechanistic model description.

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