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Steam plume length diagram for direct contact condensation of steam injected into water

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ABSTRACT

Direct Contact Condensation (DCC) of steam in water occurs when steam is introduced into water. It is a phenomenon of high importance in many industrial applications. An important feature of the DCC is the length of the steam plume. Correlations for a steam plume length presently available are accurate only for limited conditions. In this paper, a new two-dimensional steam plume length diagram is presented capable of predicting length accurately for a wide range of conditions. The diagram is validated against experiments. Furthermore, corrections necessary to adopt the diagram for steam injection into a water flow are discussed in the paper.

1. Introduction

Direct Contact Condensation (DCC) of steam injected into water is a special mode of condensation where condensation occurs on the interface between steam and water. This type of condensation forms an essential part of various applications in nuclear, chemical and marine industry. DCC can occur as condensation of steam or steam with non-condensable gases. Correct prediction and modelling of the condensation behaviour is crucial to obtain an optimised design of such devices. DCC of steam or steam with non-condensable gases may occur, for example in safety valves in boiling water reactors (Lahey and Moody, 1977; Chan et al., 1978). This paper focuses on DCC without non-condensables.

When DCC takes place there is a transfer of water vapour from gas into liquid form, causing heat, momentum and energy transfer. The transfer of mass, energy and momentum is subject to the local characteristics of the condensation process and the behaviour of the injected steam, commonly termed as a regime (Chan and Lee, 1982; Liang and Griffith, 1994; Youn et al., 2003; Petrovic de With et al., 2007), is crucial in modelling of the process of DCC.

In addition to the precise nature of the condensation regime, another important feature of DCC is the penetration distance of steam into water, the length of a steam plume. In order to calculate the heat transfer coefficient and to model DCC of steam in water the length of the steam plume is needed for a series of flow conditions of the process. However, the length of a steam plume depends on the flow conditions of the process and is therefore difficult to predict.

Various researchers have performed experiments to obtain data for length of the plume. Kerney et al. (1972) published experimental data for steam plume length when injecting steam into water through steam injectors with eight different diameters. The temperature of the water subcooling and the rate of steam injection covered a substantial range. Chun et al. (1996) published data for one steam injector and one steam inflow rate. Kim and Park (1997) presented photographic evidence from which lengths of a steam plume at two different conditions could be obtained. Kim et al. (2001, 2004) presented experimental data for three different steam injectors. Table 1 shows flow conditions at which different researchers obtained their data.

In addition to data for the steam plume length, researchers have also published empirical correlations for dimensionless plume length. These were obtained by fitting experimental data into a proposed correlation. An initial correlation for the steam plume length was derived by Kerney et al. (1972). Later studies giving further data for steam plume lengths, pointed to modifications to Kerney's original correlation.

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Nomenclature

B (−) condensation potential
c_p (J/(kg K)) specific heat at constant pressure
D (m) diameter of steam injector
G (kg/(m^2 s)) steam flow rate
h (W/(m^2 K)) heat transfer coefficient
h_{fg} (J/kg) latent heat
L (m) plume length
Re (−) steam Reynolds number
S (−) transport modulus
ΔT (K) temperature of water subcooling
η (Ns/m^2) viscosity
ρ (kg/m^3) density

Subscript
m mean value
s steam
∞ free stream conditions
0 initial conditions/at the injector

Table 1
Conditions at which data for steam plume length has been presented by different authors.

Authors	D (m)	ΔT (°C)	G_0 (kg/m^2 s)
Kerney et al. (1972)	0.0004	20–80	250–2050
	0.00079		
	0.00158		
	0.00376		
	0.00635		
	0.0095		
	0.0101		
	0.0112		
Chun et al. (1996)	0.00135	19–80	1488
Kim and Park (1997)	0.01085	77	268
		57	439
Kim et al. (2001)	0.0071	20–65	600
	0.005		870
			1045
			1188
Kim et al. (2004)	0.01085	22–84	300
			400
			500
			268
			287

Kerney et al. (1972) derived a correlation using conservation of mass for an axially symmetric steam plume with a smooth surface which gave the correlation

$$\frac{L}{D} = 0.5\frac{1}{B}\left(\frac{G_0}{G_m}\right)^{\frac{1}{2}}\frac{1}{S_m}, \qquad (1)$$

where steam inflow rate (G_0) is defined as a ratio between mass flux of steam and the steam injector exit area, parameter B is a dimensionless condensation potential $B = (c_p/h_{fg})\Delta T$ and parameter S_m a mean transport modulus $S = h/(c_p G_m)$. The constant G_m was chosen by Kerney et al. (1972) to normalize the data to 275 kg/(m^2 s). Using Eq. (1), Kerney et al. (1972) defined a dimensionless steam plume length as a function of condensation potential, a dimensionless steam mass inflow rate and mean transport modulus

$$\frac{L}{D} = f\left(B, \frac{G_0}{G_m}, S_m\right). \qquad (2)$$

Various researchers fitted their experimental data to the correlation (2) in order to obtain the functional relationship for a dimensionless steam plume length.

Kerney et al. (1972) fitted part of the data obtained during experiments into correlation (1) and obtained a slightly improved correlation by removing the restriction on powers implied by Eq. (1). Weimer et al. (1973) proposed an improvement to the correlation (2). In their experiments these researchers injected steam, vapours of ethylene glycol and vapours of iso-octane into water. They observed a correlation between plume length and density ratio of the vapour and water. They then proposed a general correlation for the dimensionless plume length for the injection of various vapours into water by adding a density ratio to Eq. (2)

$$\frac{L}{D} = f\left(B, \frac{G_0}{G_m}, \frac{\rho_s}{\rho_\infty}\right). \qquad (3)$$

Chun et al. (1996) and Kim et al. (2001) both used the correlation in Eq. (2) as proposed by Kerney et al. (1972) and using their experimental data obtained correlations.

All correlations for dimensionless steam plume length published in the literature are presented in Table 2. They have all been derived using the dimensionless equation as proposed by Kerney et al. (1972). All these predict the dimensionless steam plume length reasonably well for flow conditions at which data used to produce the individual functional relationships was obtained. However, they fail to predict steam plume length with any accuracy over a wide range of flow conditions. Therefore, there is a need for a new steam plume length prediction method, which is capable of predicting length over a wide range of flow conditions. In this paper a different approach from the one taken by researchers to date will be presented. The approach was taken in order to obtain a more generalised prediction for a steam plume length.

2. Two-dimensional steam plume length diagram

2.1. Development

In this study all the data for steam plume length available in literature was collected and used to construct the prediction unlike other researchers, who used only limited sets of data. Furthermore, correlation (2) was not used during this construction, but other ways of predicting steam plume length were proposed.

All collected data was plotted on single graphs in attempts to understand the underlying trends. First, the dimensionless steam plume length data was plotted in a graph (Fig. 1) using condensation potential B and dimensionless steam mass inflow rate G_0/G_m as axes. This method of plotting has been used by other researchers to obtain their semi-empirical correlations. Therefore, if their correlations are generally valid, the generated graph should deliver a smooth, organised distribution of data.

The dots use colour to indicate dimensionless length of the steam plume. The results show some structure but generally no clearly defined trends. The dimensionless steam plume length tends to be small for high condensation potential and large for low condensation potential.

Further graphs were then generated where the dimensionless steam plume length (L/D) and the steam plume length (L) were presented as functions of steam mass inflow rate (G_0), condensation potential (B), injector diameter (D) and steam Reynolds number ($Re = DG_0/\eta$). In addition to physical parameters, known to affect the process of DCC, the Reynolds number was chosen as one of the potential parameters. The Reynolds number is directly

Table 2
Different correlations for dimensionless steam plume length published in the literature.

Authors	Correlation L/D	Error (%)	Validity
Kerney et al. (1972)	$0.2588B^{-1}(G_0/G_m)^{0.5}$ $0.3583B^{-0.8311}(G_0/G_m)^{0.6446}$	13.6 11.7	$D = 0.00495$ m $G_0 \in (338, 1240)$ kg/(m^2 s) $B \in (0.0028, 0.135)$
Weimer et al. (1973)	$17.75B^{-1}(G_0/G_m)^{0.5}(\rho_s/\rho_\infty)^{0.5}$ $10.285B^{-0.801}(G_0/G_m)^{0.713}(\rho_s/\rho_\infty)^{0.384}$	21.9 13.0	$D = 0.00317$ m $G_0 \in (321, 1136)$ kg/(m^2 s) $B \in (0.0025, 0.063)$ $\rho_\infty/\rho_s \in (3980, 27700)$
Chun et al. (1996)	$0.5923B^{-0.66}(G_0/G_m)^{0.3444}$		$D = 0.00135$ m $G_0 = 1488$ kg/(m^2 s) $B \in (0.035, 0.15)$
Kim et al. (2001)	$0.503B^{-0.70127}(G_0/G_m)^{0.47688}$		$D = 0.005$ m $G_0 = 1188$ kg/(m^2 s) $B \in (0.037, 0.12)$

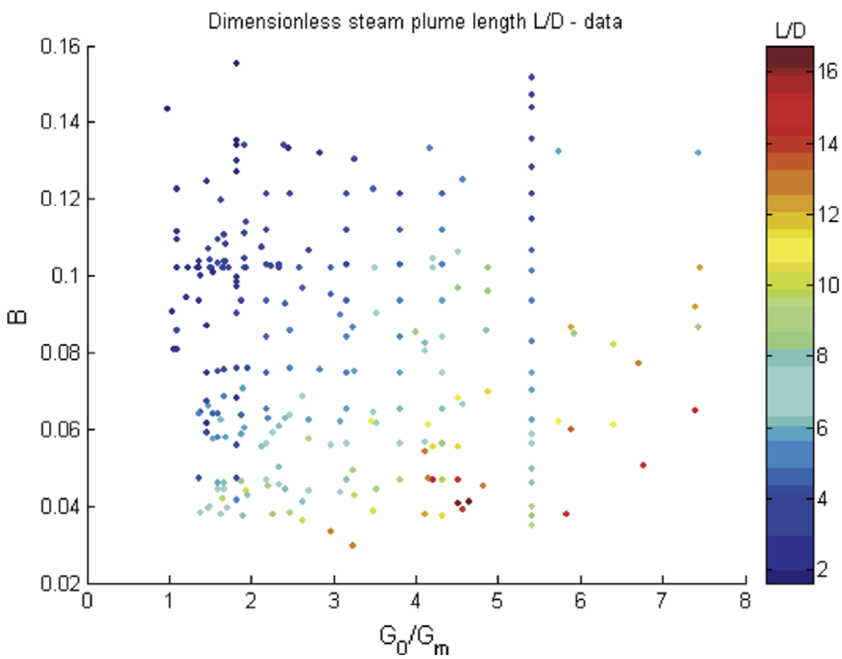

Fig. 1. Dimensionless steam plume length data as a function of dimensionless steam mass inflow rate (G_0/G_m) and condensation potential (B).

related to the inertia of injected steam and hence it should be related to the penetration length of the steam.

A much more coherent plot of the experimental data was found when using the steam plume length (L) as a function of Reynolds number (Re) and condensation potential (B) as shown in Fig. 2.

Again, the dots use colour to indicate the different lengths of the plume. Fig. 2 shows that the largest steam plume length occurs at high Reynolds numbers and low condensation potentials. The smallest lengths occur at low Reynolds numbers for all condensation potentials. The prediction is consistent with previous studies as it can be expected that the steam plume length is related to the condensation rate of steam and to the inertia of injected steam. In more detail, the steam plume extends with a higher inertia of the steam, but shortens at a higher rate of condensation. The pattern is also observed in Fig. 2.

The steam plume length data as a function of Reynolds number and condensation potential was used to develop a two-dimensional steam plume length diagram. The diagram was produced through interpolation using existing data from literature to create the generated surface. The interpolation technique used generates the surface using the method documented in Sandwell (1987). A fundamental criterion in this method is that the generated surface has to pass through all data that is provided. It is assumed that the large deviations in colours from the surrounding colours are the result of inaccuracies in the measurements, and variations in measurement techniques and setups during experiments. To produce a steam plume length diagram with better-defined trends, filtering was performed to the interpolation results which were stored in a matrix. The filtering technique used was derived by the author and includes a combination of two different filters. In the first filter a standard averaging method was applied to the neighbouring elements if these elements were dominated by scatter. In the second, a fourth order polynomial was constructed for each column and each row of the matrix. Consequently, any given element of the matrix is described by its two corresponding polynomials. In the final stage of the filtering technique, the results from both polynomials were averaged, to provide the length of the steam plume at different flow conditions.

The developed Two-Dimensional Steam Plume Length diagram is given in Fig. 3. In the pages that follow this diagram will be referred to as the "new 2DSPL diagram". It is a graphical representation of results for the steam plume length stored in a matrix. It

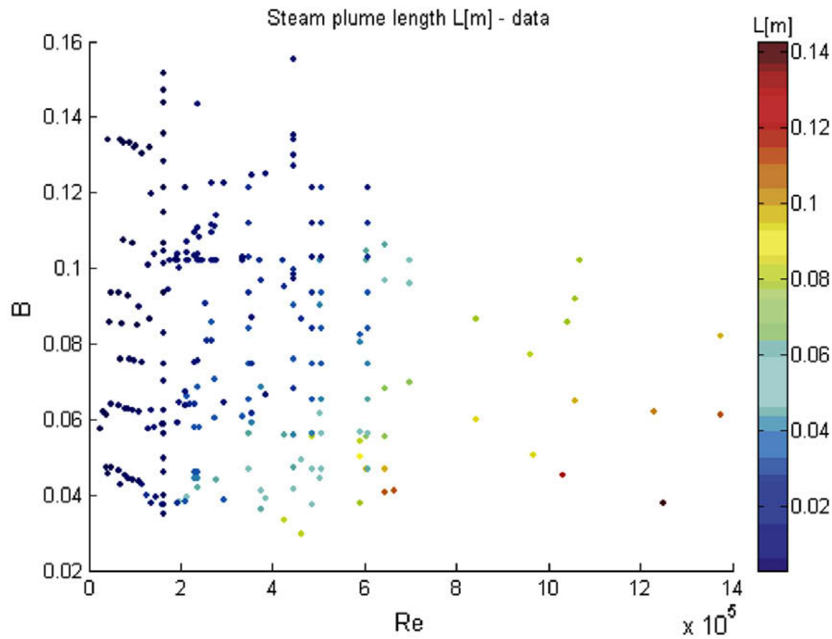

Fig. 2. Steam plume length data as a function of a Reynolds number (Re) and a condensation potential (B).

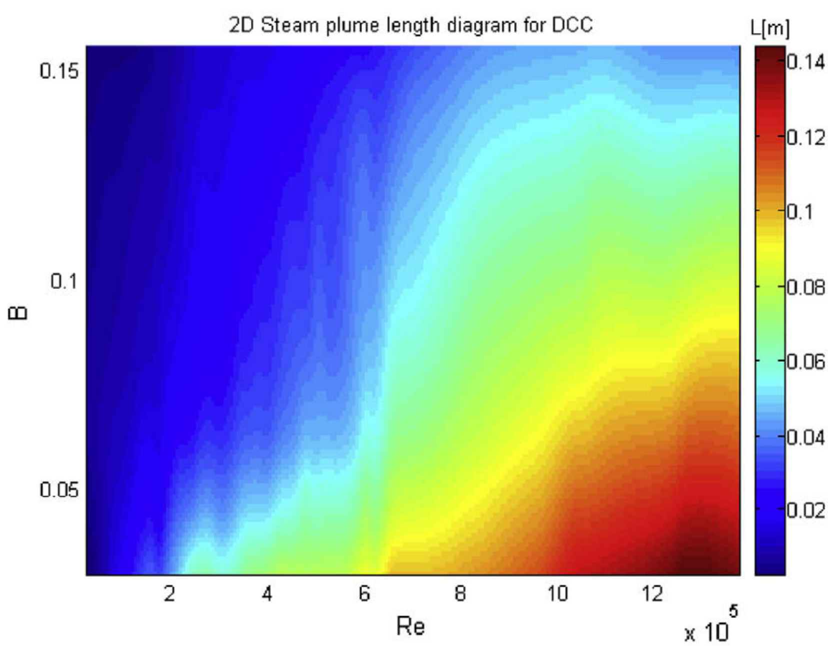

Fig. 3. New 2DSPL diagram for DCC.

shows the length of the steam plume in metres (L (m)) in relation to the steam Reynolds number (Re) in the range between 0.24×10^5 and 13.74×10^5, and the condensation potential (B) in the range between 0.029 and 0.155. Different colours on the diagram represent the length of the steam plume in metres. The maximum error of the diagram compared with original data was calculated to be 13.7%. Length of the steam plume for some values of Re and B is given in the Appendix A.

The results presented in the Fig. 3 show unexpected variations in some places, for example near $Re = 5 \times 10^5$ and $B = 0.05$. The behaviour in this region could have been smoothed out by further enhancement of the filtering procedure. However, with increased filtering one takes a risk of smoothing 'true' variations. Therefore, it is felt that with the present filtering proce-

Table 3
Calculated errors between data and plume length predictions from the new 2DSPL diagram (Fig. 3) and diagrams from correlations from literature (Fig. 4).

Authors	Error (%)
New 2DSPL diagram	13.7
Kerney et al. (1972)	28
Weimer et al. (1973)	40.5
Chun et al. (1996)	70.4
Kim et al. (2001)	43

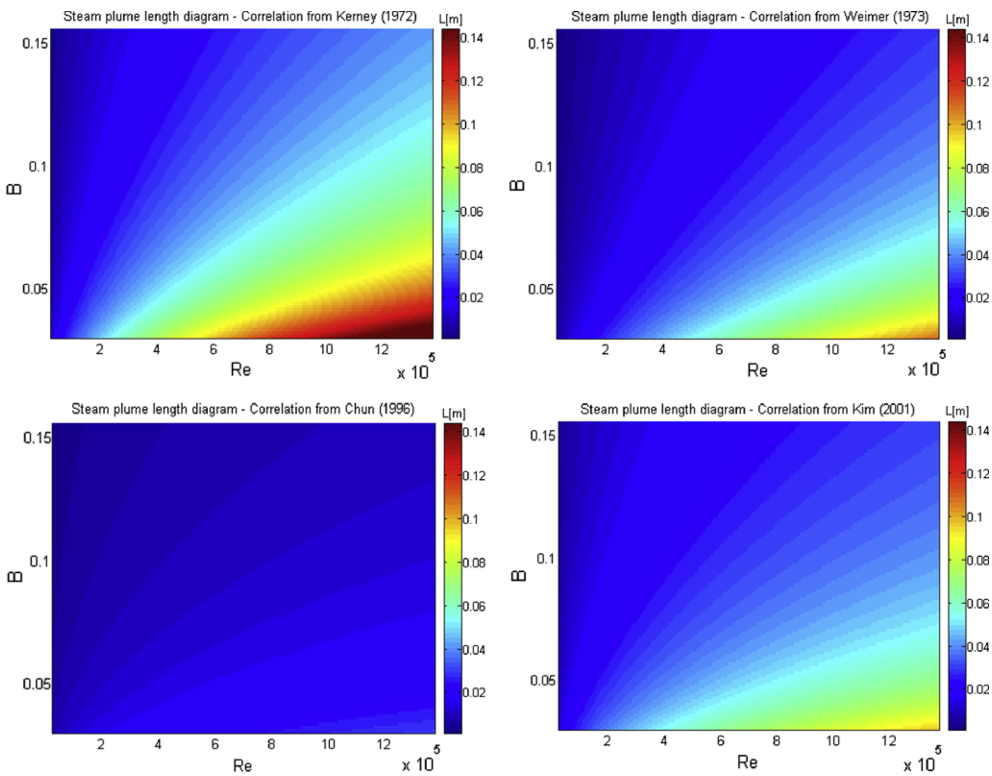

Fig. 4. Steam plume length diagram from the correlation proposed by Kerney et al. (1972) (a,upper left), Weimer et al. (1973) (b,upper right), Chun et al. (1996) (c,bottom left) and Kim et al. (2001) (d,bottom right).

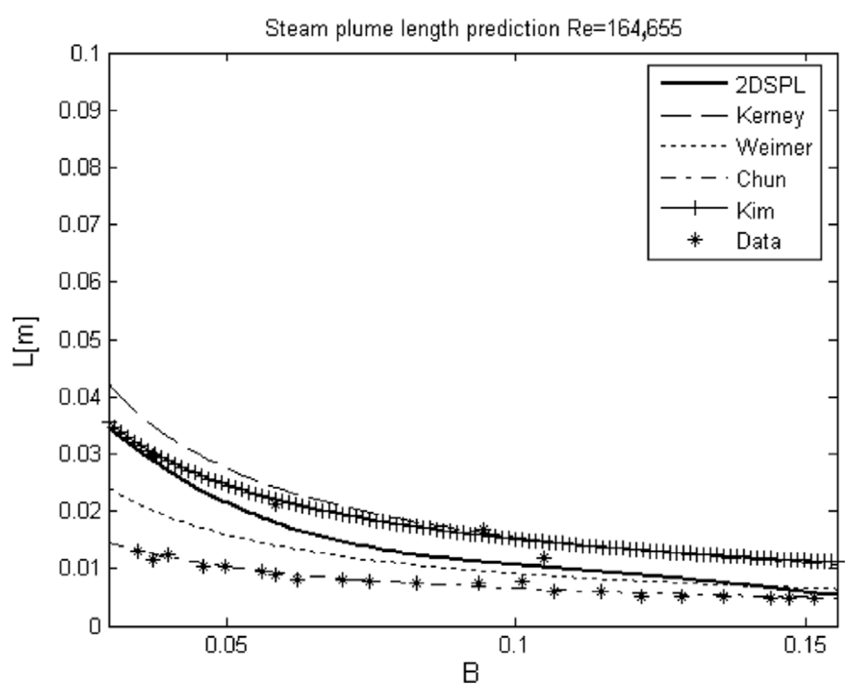

Fig. 5. Comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for $Re = 164,655$.

dure most of the variations that result from the data scatter are filtered out and the remaining variations mainly represent a physical behaviour of the process with some minor non-physical discrepancies.

The new 2DSPL diagram (Fig. 3) shows that steam develops long plumes when injected at high Reynolds numbers and short plumes at low Reynolds numbers. Furthermore, the longest plumes are to be expected at high Reynolds numbers and low condensation

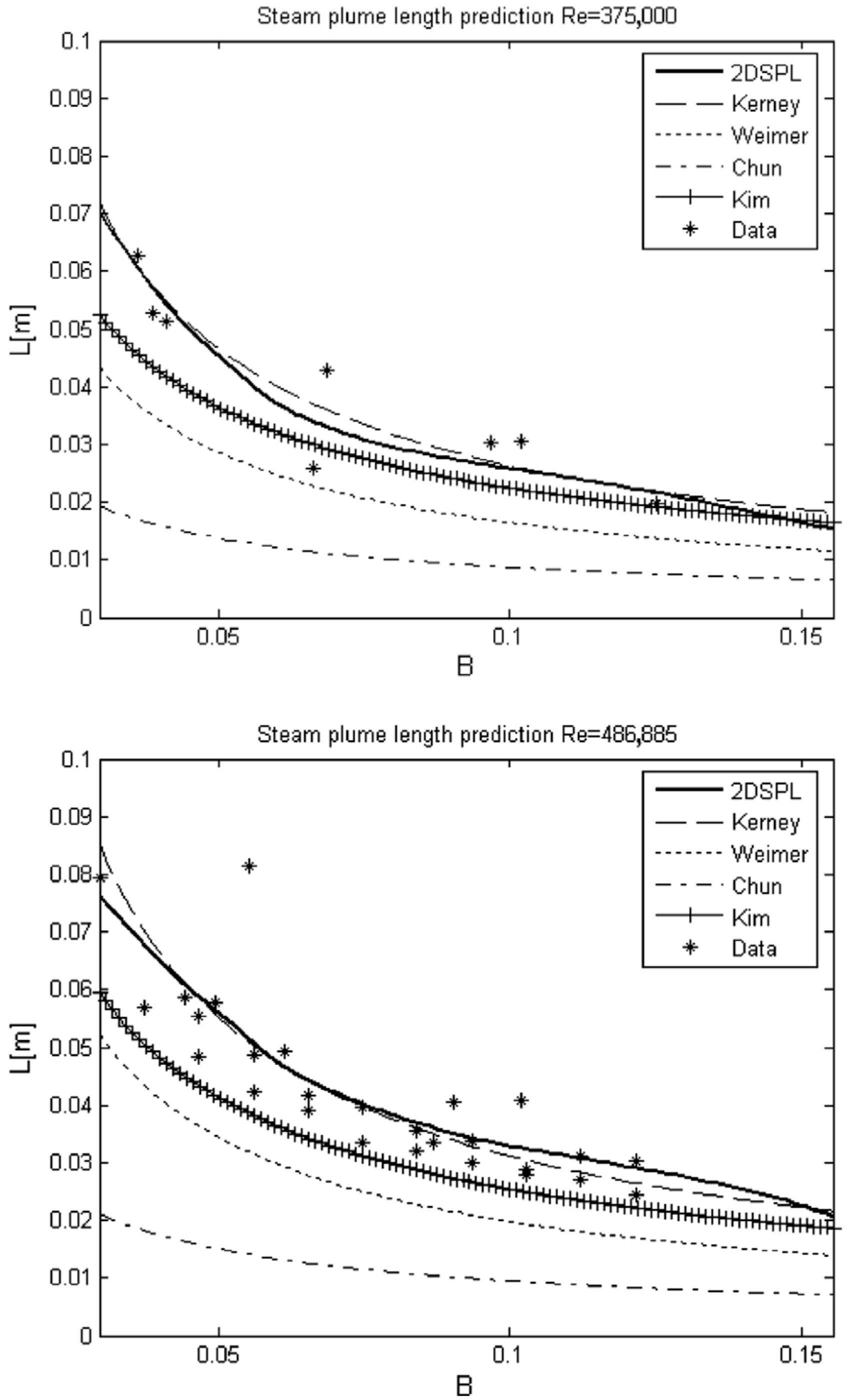

Fig. 6. Comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for (a,upper) $Re = 375,000$ and (b,bottom) $Re = 486,885$.

potentials. This is in accordance with the physics of the process which suggests that the plume is longer if the inertia of the injected steam is higher, but is shortened with increasing condensation rate.

2.2. Evaluation

The new two-dimensional steam plume length diagram (Fig. 3) was evaluated using semi-empirical steam plume length correlations from the literature (Table 2). These correlations are assumed to be valid only for specific limited conditions of flow. However, correlations were used by different researchers modelling the DCC process to predict the steam plume length also at flow conditions which differ from the specified ones (Deberne et al., 1999; Beithou and Aybar, 2000).

For the comparison with the new 2DSPL diagram, similar diagrams were generated from the correlations from literature and are presented in Fig. 4. The colours represent the length of the plume in metres and the colour range of the four diagrams in Fig. 4 was set to be the same as that in Fig. 3.

The correlations proposed by Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001) (Table 2) are all based on the original correlation proposed by Kerney et al. (1972). Each author derived modifications to Kerney's correlation based on their newly

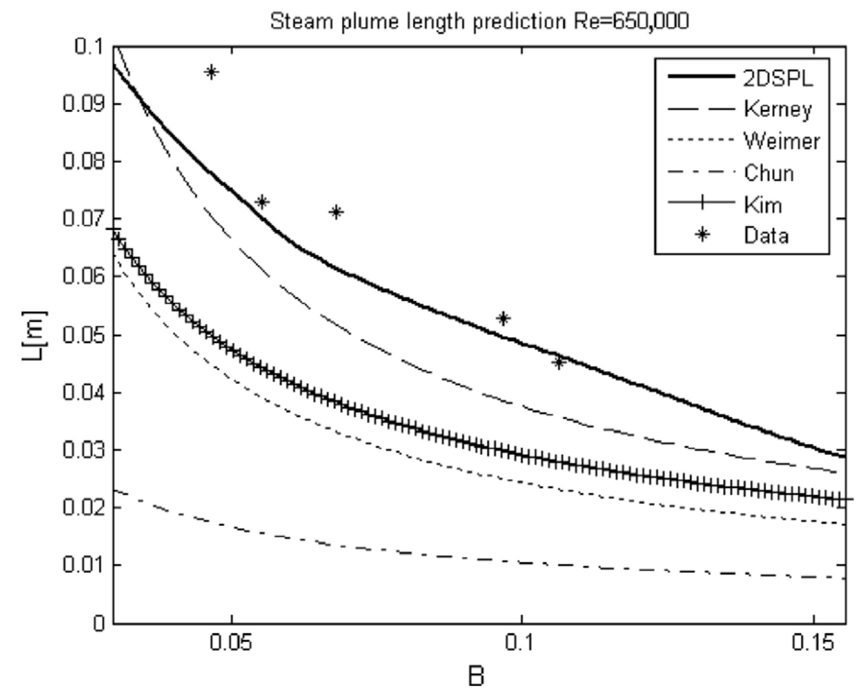

Fig. 7. Comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for $Re = 650,000$.

performed experiments. For this reason each correlation provides similar trends with varying *Re* and *B* as seen on Fig. 4. However, the length prediction differs as a result of the modification to the original correlation. The results in Fig. 4 predict the longest plume at high Reynolds numbers and small condensation potential. The shortest plume lengths are predicted at low Reynolds numbers. The longest steam plumes are predicted by the correlation suggested by Kerney et al. (1972) (Fig. 4a), whose correlation is also the most similar in prediction to the new 2DSPL diagram developed in this study. The shortest plumes are predicted by Chun et al. (1996) (Fig. 4c) and these are much lower than those in the 2DSPL diagram. Correlations from Weimer et al. (1973) (Fig. 4b) and Kim et al. (2001) (Fig. 4d) give similar predictions.

The predicted steam plume lengths from correlations proposed by earlier workers were compared with the experimental data for the steam plume length gathered in this work and shown in Fig. 2. Predictions by Kerney et al. (1972) differ the least from the experimental data and predictions by Chun et al. (1996) the most. The errors are presented on Table 3 plus that for the new 2DSPL diagram.

In addition, graphs have been produced, showing steam plume length predictions from the new 2DSPL diagram (Fig. 3), correlations from the literature (Table 2) and data from literature. The Reynolds numbers at which graphs were produced were chosen to cover the whole range of conditions and were set where data is available. Results are given in Figs. 5–7 for low Reynolds numbers and in Figs. 8 and 9 for high Reynolds numbers.

Fig. 5 shows the comparison at Reynolds number $Re = 164,655$. Here the experimental data from Chun et al. (1996) holds close agreement with the correlation he proposed. In contrast, the correlations proposed by other workers over-predict the steam plume length when compared with experimental data from Chun et al. (1996). Not enough information about the experimental setup is provided in the paper in order to establish the reason for the discrepancy. However, a correlation from Chun et al. (1996) (Table 2) is poorly dependent on the Reynolds number and it predicts lengths much lower than other correlations for a whole range of flow conditions (Fig. 4). Therefore, it is postulated that the experiments by Chun et al. (1996) are not representative for the given flow conditions.

Fig. 6 shows comparisons at Reynolds numbers $Re = 375,000$ (Fig. 6a) and $Re = 486,885$ (Fig. 6b). Here the correlation from Kerney et al. (1972) (Table 2) and the new 2DSPL diagram (Fig. 3) show similar predictions for the steam plume length for the range of condensation potentials. These predictions also correspond well with experimental data. Other correlations under-predict steam plume lengths for the whole range of condensation potentials. However, the correlation by Kim et al. (2001) (Table 2) corresponds well with experimental data for some values of condensation potential.

Fig. 7 shows the comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for $Re = 650,000$. Here steam plume lengths predicted by the new 2DSPL diagram correspond best with experimental data. All semi-empirical correlations from literature under-predict plume lengths for all values of condensation potential.

At high Reynolds numbers less experimental data is available but a comparison between predictions could still be performed and this is presented in Figs. 8 and 9. Because the predicted steam plume lengths for these flow conditions are longer, note that the vertical axis of these Figures have a greater range than that of Figs. 5–7.

Figs. 8 and 9 show, the new 2DSPL diagram gives the best prediction for all chosen Reynolds numbers. The next best is the prediction by Kerney et al. (1972). Predictions by Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001) under-predict lengths, where prediction by Chun et al. (1996) under-predicts the most. Lengths predicted by Weimer et al. (1973) and Kim et al. (2001) are similar for all values of condensation potential.

Compared with the plume lengths at low Reynolds numbers (Figs. 5–7), the lengths at high Reynolds numbers (Figs. 8 and 9) are more linearly dependent on the condensation potential. This

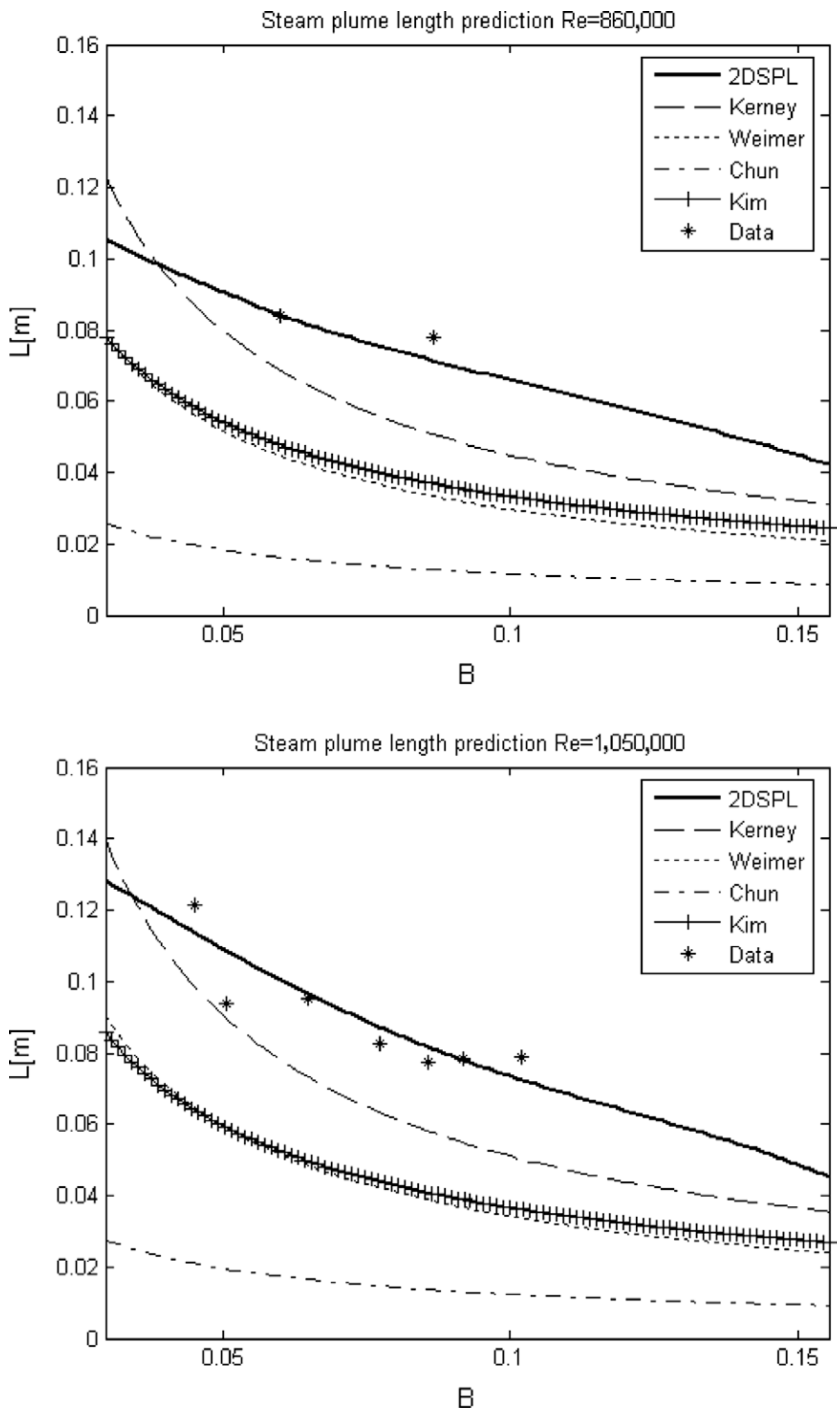

Fig. 8. Comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for (a,upper) $Re = 860,000$ and (b,bottom) $Re = 1,050,000$.

is also predicted by the new 2DSPL diagram (Fig. 3), but the semi-empirical correlations from the literature (Table 2) fail to show this difference.

The deviations of measured lengths were calculated for the eight cases presented in Figs. 5–9. The average errors are given in Table 4.

Table 4 shows that the new 2DSPL diagram gives predictions much closer to data for high Reynolds numbers compared with correlations from the literature. At Reynolds numbers below 500,000 the correlation from Kerney et al. (1972) gives similar error to that of the new diagram. The error from other correlations is higher for these conditions. At $Re = 164,655$ only the correlation by Chun et al. (1996) gives a prediction close to experimental results, but the error using correlation by Chun et al. (1996) is very high for all other Reynolds numbers.

To summarize, the developed two-dimensional steam plume length diagram (Fig. 3) outperforms the semi-empirical correlations from the literature (Table 2) for a wide range of flow conditions. The new 2DSPL diagram could still be improved when new experimental data becomes available. This would be of special benefit at high Reynolds numbers, where only a limited amount of data is available.

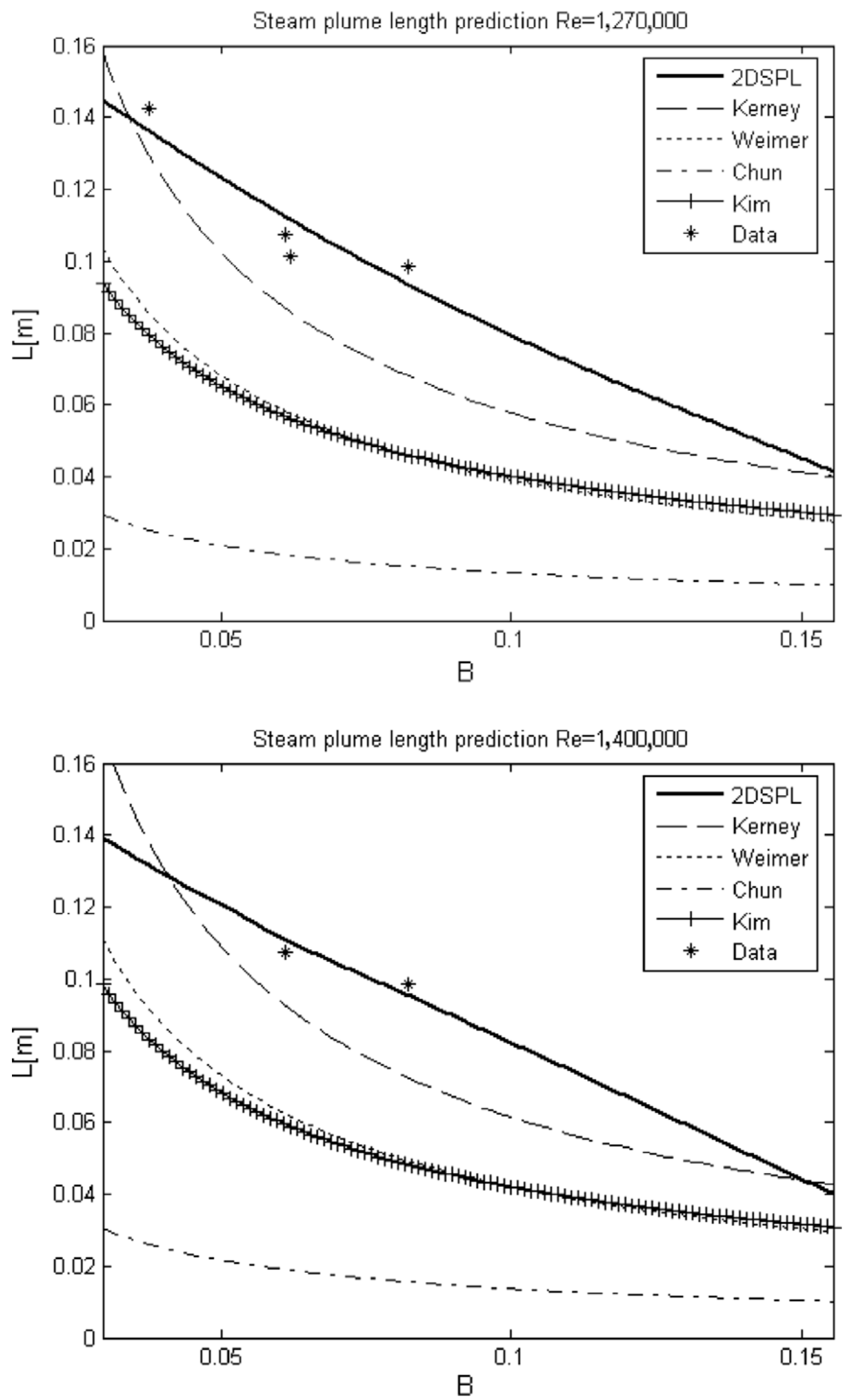

Fig. 9. Comparison between steam plume length predictions from the new 2DSPL diagram, correlations from Kerney et al. (1972), Weimer et al. (1973), Chun et al. (1996) and Kim et al. (2001), and experimental data for (a,upper) $Re = 1,270,000$ and (b,bottom) $Re = 1,400,000$.

Table 4
Calculated errors (%) between data and plume length predictions from the new 2DSPL diagram and semi-empirical correlations from literature for different Reynolds numbers.

Re	Error in prediction (%)				
	2DSPL	Kerney et al. (1972)	Weimer et al. (1973)	Chun et al. (1996)	Kim et al. (2001)
164,655	69.7	131.3	46	13.2	119.2
375,000	14.3	14.8	35.7	68	20
486,885	11.8	11.1	35.1	70.3	29.4
650,000	12.2	23.6	51.2	80.3	44.3
860,000	4.1	26.4	51.9	82.1	47.8
1,050,000	6.3	22.5	48.7	82.4	47
1,270,000	6	18.4	45.5	83	47.2
1,400,000	3	19.8	45.8	83.2	47.6

Table 5
Observed lengths of steam plume with injection into a water flow.

B	*Re*	*L* (m)	
0.158815	173,934	0.003	Water flow
0.158815	217,409	0.0035	Water flow
0.158815	434,852	0.007	Water flow
0.158815	217,409	0.01	Stagnant water

3. Two-dimensional steam plume length diagram applied to DCC in a water flow

The developed 2DSPL diagram gives good predictions for the injection of steam into a stagnant water. However, it is expected, that the steam plume length is affected by the movement of the water. When steam is injected into a water flow, the plume is affected by the combined momentum of the injected steam and the water flow. Furthermore, the plume is also affected by the constant supply of cold water around the steam plume causing the steam to condense faster. Hence, the 2DSPL diagram for an injection of steam into a water flow will probably differ from the 2DSPL diagram for stagnant water.

Experiments were performed (Petrovic de With et al., 2007; Petrovic-de With, 2006) in which steam was injected at the centre of a pipe with a steady flow of cold water. The centreline velocity of the water flow just upstream of the point of steam injection was 1.9 m/s and temperature difference between injected steam and water flow was 85 °C. The diameter of the pipe was much larger than the generated steam plumes. Steam was injected at three different Reynolds numbers through steam injectors with three different diameters 5 mm, 4 mm and 3 mm.

The experiments were repeated several times for each flow condition. Table 5 gives average observed plume lengths at different Reynolds numbers. In addition to measuring the plume length with water flow with 4 mm injector diameter, measurements were also made under the same conditions but with the water flow temporarily stopped to give the stagnant state. A significant increase in a length of a steam plume was observed when there was no flow.

The lengths of steam plume given in Table 5 are compared with predictions using the new 2DSPL diagram in Fig. 10.

Fig. 10 shows that the plume lengths are here much shorter when steam is injected into a water flow instead of stagnant water. However, with stagnant water the plume extends and the length is in good agreement with the length proposed by the new 2DSPL diagram.

Calculations show that the length of the steam plume decreased by 60–65% for all three Reynolds numbers when steam was injected into a water flow. This shows that the effect of increased condensation due to the constant supply of fresh water is much larger than the momentum effect of the water flow. Hence, heat and mass transfer due to condensation seem to affect the steam plume more than the momentum of the injected steam. This agrees with previous observations where it was found that more steam is needed to achieve jetting in a water flow than in stagnant water.

It is likely that different centreline velocities of water flow would cause different decreases of the steam plume length. Therefore, it is desirable that more experiments should be performed at various condensation potentials, Reynolds numbers and velocities of water flow.

4. Conclusions

In this paper, a new two-dimensional steam plume length diagram for DCC of steam injected into stagnant water has been presented. The study showed, that the steam plume length is a function of a steam Reynolds number and condensation potential. The developed diagram is incorporating all steam plume experimental data available to date and is capable of predicting plume length with good accuracy for a wide range of steam flow conditions. This gives an advantage over the correlations for dimensionless plume length found in literature which can only predict lengths correctly for limited conditions.

The predictions from the new 2DSPL diagram have been compared with those from semi-empirical correlations from the literature. The comparison shows that the 2DSPL diagram accurately predicts lengths at both high and low Reynolds numbers. The

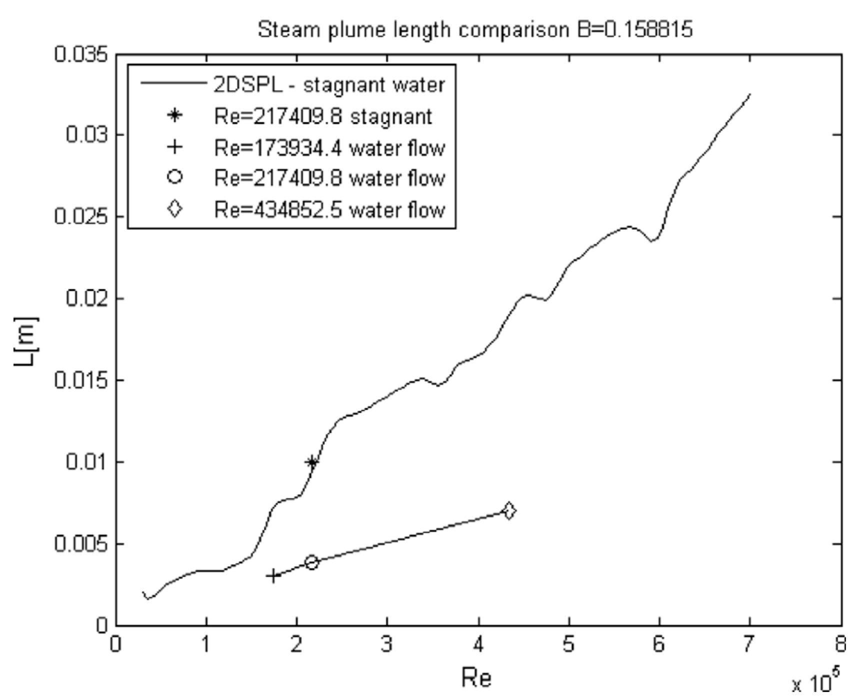

Fig. 10. Comparison between plume length predictions from new 2DSPL diagram for stagnant water and experimental data for injection into a water flow.

semi-empirical correlations were derived from experiments performed at low Reynolds numbers and therefore are not capable of predicting accurately lengths at high Reynolds numbers. More experimental data to more firmly establish the soundness of the new 2DSPL diagram at high Reynolds numbers would be useful but this would be unlikely to change the general structure of the diagram.

Data for DCC of steam into a water flow showed that the length of the plume decreases in comparison with the no-flow conditions. For a water flow with a centreline velocity of 1.9 m/s the length decreased by around 60–65% for three different Reynolds numbers. Predictions of length using the new 2DSPL diagram over-estimated the plume length by this amount. More experiments should be performed to fully understand the effect of water flow on a steam plume. Furthermore, effects of non-condensable gases added to the steam should be investigated.

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Appendix A. Steam plume length table

Length of the steam plume in metres (L (m)) for different steam Reynolds numbers $Re = DG_0/\eta$ and condensation potentials $B = (c_p/h_{fg})\Delta T$, where $\eta = 12.2 \times 10^{-6}$ Ns/m^2, $c_p = 4.217$ kJ/(kg K) and $h_{fg} = 2257$ kJ/kg. (Table A.1 for small values of B and Table A.2 for large values of B.)

Table A.1
Length of a steam plume in metres (L (m)) at different Reynolds numbers and condensation potentials for small values of B.

$Re \times 10^{-5}$	B					
	0.0297	0.0401	0.0516	0.0631	0.0746	0.0861
0.2439	0.00335	0.00278	0.00480	0.00650	0.00648	0.00606
0.7984	0.01534	0.01377	0.01203	0.01091	0.00950	0.00835
1.4145	0.03310	0.02678	0.02098	0.01673	0.01373	0.01171
2.0306	0.04462	0.03652	0.02910	0.02325	0.01939	0.01663
2.6466	0.06395	0.04926	0.03752	0.02925	0.02480	0.02213
3.2627	0.06156	0.04961	0.03964	0.03186	0.02770	0.02495
3.8788	0.07185	0.05566	0.04351	0.03495	0.03109	0.02881
4.4949	0.07695	0.06207	0.05039	0.04141	0.03695	0.03394
5.1110	0.07751	0.06580	0.05538	0.04614	0.04099	0.03734
5.7270	0.08224	0.06917	0.05819	0.04908	0.04447	0.04159
6.3431	0.09185	0.07897	0.06838	0.05937	0.05415	0.04994
6.9592	0.09798	0.08825	0.07855	0.06906	0.06261	0.05736
7.5753	0.09953	0.09091	0.08234	0.07393	0.06795	0.06281
8.1914	0.10277	0.09485	0.08699	0.07944	0.07378	0.06878
8.8074	0.10727	0.09964	0.09178	0.08432	0.07827	0.07288
9.4235	0.11265	0.10473	0.09644	0.08880	0.08219	0.07623
10.0396	0.12241	0.11379	0.10410	0.09512	0.08686	0.07951
10.6557	0.12924	0.11906	0.10830	0.09902	0.09053	0.08313
11.27171	0.13277	0.12304	0.11241	0.10307	0.09408	0.08594
11.8878	0.13703	0.12632	0.11469	0.10441	0.09459	0.08571
12.5039	0.14406	0.13261	0.12016	0.10886	0.09825	0.08860
13.1200	0.14348	0.13317	0.12203	0.11135	0.10153	0.09222
13.7361	0.13927	0.12936	0.11940	0.10931	0.10082	0.09243

Table A.2
Length of a steam plume in metres (L (m)) at different Reynolds numbers and condensation potentials for large values of B.

$Re \times 10^{-5}$	B					
	0.0977	0.1092	0.1207	0.1322	0.1437	0.1553
0.2439	0.00584	0.00528	0.00464	0.00392	0.00315	0.00251
0.7984	0.00766	0.00694	0.00623	0.00541	0.00437	0.00309
1.4145	0.01047	0.00954	0.00870	0.00765	0.00614	0.00389
2.0306	0.01464	0.01311	0.01182	0.01062	0.00938	0.00797
2.6466	0.02036	0.01898	0.01753	0.01597	0.01436	0.01291
3.2627	0.02293	0.02137	0.01978	0.01817	0.01651	0.01488
3.8788	0.02703	0.02527	0.02299	0.02044	0.01797	0.01626
4.4949	0.03152	0.02934	0.02683	0.02426	0.02186	0.02013
5.1110	0.03471	0.03283	0.03092	0.02886	0.02619	0.02252
5.7270	0.03976	0.03847	0.03670	0.03416	0.03021	0.02432
6.3431	0.04620	0.04264	0.03870	0.03474	0.03097	0.02789
6.9592	0.05313	0.04966	0.04619	0.04252	0.03804	0.03214
7.5753	0.05840	0.05447	0.05046	0.04634	0.04177	0.03653
8.1914	0.06428	0.06005	0.05561	0.05098	0.04596	0.04050
8.8074	0.06802	0.06344	0.05874	0.05387	0.04863	0.04294
9.4235	0.07082	0.06567	0.06052	0.05527	0.04980	0.04413
10.0396	0.07305	0.06720	0.06173	0.05634	0.05076	0.04471
10.6557	0.07664	0.07064	0.06490	0.05905	0.05278	0.04588
11.27171	0.07852	0.07152	0.06488	0.05835	0.05180	0.04523
11.8878	0.07760	0.07002	0.06292	0.05605	0.04927	0.04257
12.5039	0.07972	0.07146	0.06370	0.05623	0.04884	0.04148
13.1200	0.08324	0.07457	0.06611	0.05783	0.04967	0.04176
13.7361	0.08393	0.07537	0.06652	0.05764	0.04876	0.04027

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