مجلة جامعة تشرين للبحوث والدراسات العلمية _ سلسلة العلوم الهندسية المجلد (30) العدد (5) 2008
Tishreen University Journal for Research and Scientific Studies - Engineering Sciences Series Vol. (30) No. (5) 2008

Particulate Fouling Effect on Heat Exchanger Performance

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(Received 6 / 1 / 2008. Accepted 16 / 6 / 2008)

□ ABSTRACT □

The previous work proves that there is no reliable correlation to predict particulate fouling effect on heat exchangers performance. The main objective of this work is to develop a semi-empirical model for heat exchanger fouling.. The available experimental data are analyzed and then used to establish the proposed model. This model accounts for the effects of flow conditions on fouling. Resistance to predict the design, operation and performance parameters of plate type heat exchangers. It is found that the exchanger effectiveness decrease by 11% to 32.5% due to fouling of the present conditions. Also, the predicted pressure drop with fouling is higher than that of the clean fluids by 15% to 75% for the same conditions. Therefore, extra power and initial operating costs are needed. The present model can be used to document the design parameters of plate type, double pipe, and similar heat exchangers.

Keywords: predictions, particulate fouling, heat exchanger performance, heat transfer

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مجلة جامعة تشرين للبحوث والدراسات العلمية _ سلسلة العلوم الهندسية المجلد (30) العدد (5) 2008
Tishreen University Journal for Research and Scientific Studies - Engineering Sciences Series Vol. (30) No. (5) 2008

تأثير الترسبات الجزيئية في كفاءة المبادلات الحرارية

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(تاريخ الإيداع 6 / 1 / 2008. قُبِل للنشر في 2008/6/16)

□ الملخّص □

تبين مما سبق أنه لا توجد علاقة عامة أو موثقة لدراسة تأثير الترسبات الجزئية في أداء المبادلات الحرارية. الهدف الرئيس من البحث الحالي هو تطوير نموذج شبه عملي لدراسة تأثير الترسيب في أداء المبادلات الحرارية والتنبؤ بزمن فترات التنظيف المتعاقبة. لقد تم تقييم نتائج الأبحاث التجريبية السابقة وتحليلها لاستنتاج النموذج المقترح مع الأخذ بعين الاعتبار تأثير ظروف الجريان مثل السرعة، التركيز، و التدفق الحراري في مقاومة الترسيب، معامل انتقال الحرارة الإجمالي، مساحة سطح التسخين، كفاءة المبادل و الفقد في الضغط، الخ.

تم تطبيق النموذج الرياضي على مبادلات حرارية من النوع الصفائحي لدراسة عناصر التصميم والأداء ضمن مجال واسع لظروف التشغيل. أثبت البحث أن كفاءة المبادل الحراري تتناقص تقريبا بمقدار 11% إلي 32.5% في ظل ظروف التشغيل الحالية نتيجة هذه الترسبات، كما تم التنبؤ بقيمة الفقد في الضغط الناتج عن هذه الترسبات، والتي تزداد عن مثيلتها في الحالة النظيفة تقريبا بمقدار 15% إلي 75% في ظل ظروف التشغيل نفسها، من أجل ذلك يحتاج نظام الضخ إلي طاقة إضافية وبالتالي تكلفة تشغيل.

الكلمات المفتاحية: الاتساخ الجزيئي، انتقال الحرارة، المبادلات الحرارية.

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NOMECLATURE:

C_b	:	bulk particle concentration, ppm
q_o	:	initial heat heat flux, kW/m^2
R_f	:	fouling resistance, $(m^2.K)/kW$
R_f^*	:	asymptotic fouling resistance, $(m^2.K)/kW$
$R^*_{f,C}$	:	asymptotic fouling resistance in terms of particle concentration, $(m^2.K)/k W$
$R^*_{f,q}$	:	asymptotic fouling resistance in terms of heat flux, $(m^2.K)/kW$
$R^*_{f,u}$	:	asymptotic fouling resistance in terms of flow average velocity, $(m^2.K)/kW$
t	:	time, s
U	:	overall heat transfer coefficient of fouled fliud, $kW/(m^2 \cdot K)$
U_o	:	overall heat transfer coefficient of clean fliud, $kW/(m^2 \cdot K)$
u	:	fouled flow average velocity, m/s
u_o	:	clean flow average velocity, m/s
b	:	time constant, 1/min
b_c	:	time constant in terms of particle concentration, 1/s
b_q	:	time constant in terms of heat flux, 1/s
b_u	:	time constant in terms of flow average velocity, 1/s
Dp	:	pressure drop of fouled flow, Pa
Dp_o	:	pressure drop of clean flow, Pa
e	:	exchanger effectiveness for fouled flow, dimensionless
e_o	:	exchanger effectiveness for clean flow, dimensionless
X-2	:	fouled fluid (for composition see Muller-Steinhagen and Middlis, 1989)

INTRODUCTION:

Fouling is considered one of the most important problems in many engineering applications, especially in heat transfer equipment. Fouling of such equipment is defined as the deposition of unwanted materials on heat transfer surfaces. Such deposit causes degradation in thermal and hydraulic performance of the equipment. Therefore, prediction of fouling (especially particulate fouling) is necessary for design, operation and performance of heat exchangers.

Particulate fouling is studied experimentally in several engineering applications. The experimental data of such investigations are quite useful to understand this important phenomenon. For example, Blochl and Muller-Steinhagen (1990) studied the influence of particulate fouling in a vertical annular test section. Bott and Bemrose (1981) measured the effect of particulate fouling in the gas side of finned tube heat exchangers. Chamra and Webb (1993) investigated particulate fouling in plain and enhanced tubes. Freeman et al., 1990 measured particulate fouling on the outer surface of finned and rough tubes in double pipe heat exchangers. Kim and Webb (1990) and (1991) studied the effect of roughness on particulate fouling. Middis and Muller-Steinhagen, 1990 investigated the effect of particulate fouling of smooth, artificially roughened and corrugated heat transfer surfaces of plate type heat exchangers. Muller-Steinhagen and Middis (1989) studied the effect of particulate fouling on plate heat exchangers. Muller-Steinhagen and Blochl, (1988) investigated the effect of particulate fouling in annular heat exchangers. Muller-Steinhagen et al. (1986) and (1988) studied the effect of particulate fouling during boiling and sensible heat transfer. Somerscales et al (1991) investigated the effect of particulate fouling on heat transfer of internally enhanced tubes. The water quality effect on particulate fouling was studied by Warkinson (1983). Webb and Chamra (1991) performed particulate fouling tests in enhanced and plain tubes while Webb and Kim (1989) investigated the effect of particulate fouling in commercial tubes. Zhang et al. (1990) and (1992) measured particulate fouling on plate finned-tube automotive heat exchangers in order to enhance the heat transfer rate.

The first theoretical significant attempt to derive a general fouling model was by Kern and Seaton (1959). They observed that the experimental data of fouling curves follow a typical pattern after an initial period of fast fouling build-up. They also observed that the fouling resistance tends to remain constant. Watkinson and Epstein, (1970) and (1988) extended the model of Kern and Seaton (1959) by incorporating a sticking probability in their deposition model. Recently, Chamra and Webb (1994) and (1998) modeled the liquid side particulate fouling in enhanced and plain tubes. The removal rate of particulate fouling was modeled by Epstein (1988). Gudmundsson (1981) identified three main deposition regimes, namely diffusion, inertia and impaction. Kim and Webb (1991) modeled particulate fouling of water in tubes having two-dimensional roughness. Pinheiro (1988) summarized particulate fouling models of the once through heat exchangers.

The goal of this work is to develop a semi-empirical model to predict the effects of the actual operating conditions on particulate fouling of plate type heat exchangers since there is no reliable or generalized model is available. The available experimental results are first assessed, analyzed and then used to develop the present model. This model incorporates the effect of time, flow velocity, particle concentration and heat flux on the design, operation and performance of plate type heat exchangers. The model can also do the same predictions for double pipe heat exchangers. The developed model can be used as a fast and inexpensive tool to document the details of particulate fouling effect on plate type, double pipe and the similar heat exchangers.

Materials and Methods:

Kern and Seaton (1959) described the behavior of fouling resistance, R_f experimental data by the following model

$$R_f = R_f^* (1 - e^{-bt}) \qquad (1)$$

where, R_f^*: asymptotic fouling resistance, t is the time and b is the time constsnt. Pinheiro, 1988 summarized the proposed dependence of R_f^* and b on fouled flow average velocity, u, of several investigators. His summary shows that R_f^* is proportional to 1/u or $1/u^2$ or $1/u^3$ and b is proportional to u or u2 based on theoretical studies. Muller-Steinhagen and Middis, 1989 suggested that R_f^* is proportional to $u^{-1.8}$ based on their experimental study using plate type heat exchanger. The present model is the same as that of Kern and Saton (1959) and only expressions for R_f^* and b of equation (1) are obtained from the experimental data of Muller-Steinhagen and Middis (1989) shown in Figs 1 to 3 for plate type heat exchangers. These data are for a fouled fluid X-2 (for composition see Muller-Steinhagen and Middis (1989) and water as the clean fluid. These experimental data are assessed and analyzed first and then used to develop the required expressions. The asymptotic fouling resistance, $R^*_{f,u}$, and time constant, b_u, in terms of the flow average velocity, u_o, are obtaind from the experimental data shown in Fig. 1 as:

$$R^*_{f,u} = a_o + a_1 u_o + a_2 u_o^2 \quad (2)$$

and

$$b_u = b_o + b_1 u_o + b_2 u_o^2 \quad (3)$$

In the same way, The asymptotic fouling resistance, $R^*_{f,c}$, and the time constant, b_c, as a function of bulk particle concentration. C_b, are obtained from experimental data shown in Fige. 2 as:

$$R^*_{f,c} = a_o + a_1 C_b + a_2 C_b^2 \quad (4)$$

and

$$b_c = b_o + b_1 C_b + b_2 C_b^2 \quad (5)$$

Similarly, the asymptotic fouling resistance, $R^*_{f,q}$, and the time constant, b_q, as function of the initial heat flux, q_o, are obtained from the experimental data shown in Fig. 3 as

$$R^*_{f,q} = a_o + a_1 q_o + a_2 q_o^2 \quad (6)$$

and

$$b_q = b_o + b_1 q_o + b_2 q_o^2 \quad (7)$$

The constants a_o, a_1, a_2, b_o, $b_1$and b_2 of the above equations are given in Tables I and II. The general expressions of R^*_f and □ in terms of clean flow average velocity, bulk particle concentration and initial heat flux is developed from the correlations (2) through (7) using the experimental data shown in Figs 1, 2 and 3 as

$$R^*_f = c_o + c_1 R^*_{f,u} + c_2 R^{*2}_{f,u} + c_3 R^*_{f,c} + c_4 R^{*2}_{f,c} + c_5 R^*_{f,q} + c_6 R^{*2}_{f,q} \quad (8)$$

and

$$b = e_o + e_1 b_u + e_2 b_u^2 + e_3 b_c + e_4 b_c^2 + e_5 b_q + e_6 b_q^2 \quad (9)$$

The constants c_o, c_1, c_2, c_3, c_4, c_5, c_6, e_o, e_1, e_2, e_3, e_4, e_5, and e_6 are given in Table III. The developed model covers a wide range of the actual operating conditions and can be used for plate type, double pipe and the similar heat exchangers.

RESULTS AND DISCUSSION:

The semi-empirical model developed for particulate fouling is used to predict the performance, design and operation parameters of plate type and double pipe heat exchangers. The model predictions cover a wide range of the actual operating conditions, namely the time, flow velocity, bulk particle concentration and initial heat flux.

The experimental data in Figs. 1, 2 and 3 are used to develop the present model. These data are for different flow average velocity, bulk particle concentration and initial heat flux. The prediction of the present model for such operating conditions are also shown in these figures.

Comparison with Previous Results:

The predictions of the present model are compared with the available experimental data. Figure 4 shows the comparison of predictions against the experimental data of Muller-Steinhagen and Muddis (1989) and Muller-Steinhagen et al. (1988) for plate type heat exchangers. This figure shows the variation of the asymptotic fouling resistance versus the flow average velocity and bulk particle concentration. It is seen that the asymptotic fouling resistance increases with bulk particle concentration and decreases with flow average velocity. It is clear that the present model predicts the experimental data with good agreement. Figure 5 shows the comparison between the present prediction and experimental data of Muller-Steinhagen and Muddis, (1989) for plate type heat exchangers. It is seen that the predicted dimensionless overall heat transfer coefficient is also in good agreement with experimental data.

For double pipe heat exchangers, the present model predictions are compared with the experimental results of Blochl and Muller-Steinhagen (1990) in Fig. 6. This figure shows the variation of fouling resistance versus time and bulk particle concentration. It is clear from this figure that both the experimental and prediction data follow an exponential behavior until they asymptote to certain values. The rate of fouling, dR_f/dt, is seen to be smaller than that of plate type heat exchangers and lager than that of double pipe heat exchangers. This is due to higher removal rate of deposited fouling in case of round pipes. It is seen from this figure that the model over predicts the experimental data. This is because the flow near the corners of the flow area in case of plate type exchangers allows more fouling deposition compared with that in round pipes. The more fouling deposition near the corners is due to the decreased flow average velocity and secondary flow there. Therefore, the present model can be used as a quick and cheap tool to document the predictions of such heat exchangers and the similar ones. In the following section, the effect of time, flow average velocity, bulk particle concentration and initial heat flux are investigated for plate type heat exchangers

Effect of Time:

The variation of experimental and predicted data of fouling resistance with time is shown in Figs. 1, 2 and 3 for different flow average velocity, particle concentration and heat flux. It seen that the fouling resistance of both data increases with time exponentially until it asymptotes to a certain value. It is seen from these Figs. 1 and 2 that the rate of fouling, dR_f/dt, increases as the flow average velocity decreases or as the particle concentration increases.

The variation of predicted heat exchanger effectiveness ratio, e/e_o, and dimensionless pressure drop, Dp/Dp_o, versus time is shown in Figs. 7 and 8 for different flow velocities (0.3 to 0.5 m/s). For constant velocity, the effectiveness decreases exponentially with time and asymptotes to a constant value as seen in Fig. 7. The predicted dimensionless pressure drop increases exponentially with time until it asymptotes to a constant value for a specific velocity. The decrease of effectiveness ratio results from the increase of fouling accumulation of deposition with time, which increases the thermal resistance for heat transfer. The increase of pressure drop is due to the increase of fouling thickness, which results in higher flow average velocity for the same flow rate. As well, the deposition of fouling increases the surface roughness. Similar behavior of predictions for different particle concentrations and heat fluxes is shown in Figs. 9 to 12.

Effect of Flow Velocity:

The effect of flow average velocity on both the experimental and predicted fouling resistance is shown in Fig. 1. It is clear form Fig. 1 and 4 that the asymptotic fouling resistance of both data increases as the flow average velocity decreases. As well, the rate of fouling, dR_f/dt, in the starting period increases with the flow average velocity.

The variation of exchanger effectiveness and pressure drop ratios with time is shown in Figs. 7 and 8 respectively. This is for initial heat flux and bulk particle concentration of 40 kW/m^2 and 400 ppm respectively and for different flow average velocities (0.3 to 0.5 m/s). It is clear from these figures that the predictions decrease or increase exponentially. The asymptotic effectiveness ratio decreases as the flow average velocity decreases. The asymptotic values of $\varepsilon/\varepsilon_o$ is in the range of 0.74 to 0.89 for the shown range of flow average velocity. The more decrease in $\varepsilon/\varepsilon_o$ is due to the more deposition and the less removal of fouling by lower flow average velocity, which increases the heat transfer thermal resistance. On the other hand, the asymptotic pressure drop ratio increases as the flow average velocity decreases. The net increase in pressure drop or decrease in exchanger effectiveness shown in Figs. 7 and 8 is controlled by the deposited foulant roughness, deposition rate, removal rate and flow average velocity. The asymptotic values of pressure drop ratio are in the range of 1.15 to 1.5 for the shown average velocity range. This means that an extra pumping power of about 15 to 50% is needed for fouled flow circulation under the present flow conditions compared with non fouling (clean) flow. This adds an extra initial cost to the pumping system and also increases the operating cost due to extra power consumption.

Effect of Particle Concentration:

The effect of bulk particle concentration on both experimental and predicted fouling resistance shown in Fig. 2. It is clear from Figs. 2 and 4 that the asymptotic fouling resistance of both data increases as the bulk particle concentration increases and the rate of fouling, dR_f/dt, in the starting period increase as the bulk particle concentration increases.

The change of exchanger effectiveness and pressure drop ratios with time and bulk particle concentration is shown in Figs. 9 and 10 for an initial heat flux and flow average velocity of 40 kW/m^2 and 0.4 m/s respectively. The behavior of predictions and discussion are the same as for Figs. 7 and 8 to some degree with one exception. As the bulk particle concentration decreases, the asymptotic effectiveness ratio increases while the asymptotic pressure drop ratio decreases. The asymptotic effectiveness and pressure drop ratios are in the range of 0.675 to 0.8 and 1.25 to 1.75 respectively for bulk particle concentration in the range of 400 to 900 ppm and for the present operating conditions.

Effect of Heat Flux:

The effect of initial heat flux on both experimental and predicted fouling resistance is shown in Fig. 3. It is clear that the asymptotic fouling resistance increase with initial heat flux to a certain value and then decreases again. It is clear from Figs. 1 to 3 that the effect of initial heat flux on fouling is small compared with the effect of flow velocity and particle concentration.

The behavior of exchanger effectiveness and pressure drop ratios with time and initial heat flux are displayed in Figs. 11 and 12 for a bulk particle concentration and flow average velocity of 400 ppm and 0.4 m/s respectively. Again, the variation seen in these figures is exponential behavior either decreasing or increasing for constant initial heat flux. It is clear that the asymptotic effectiveness ratio decreases as the initial heat flux increases until it reaches a minimum value at a heat flux of 30 kW/m^2 and then increases again. This behavior is confirmed experimentally by Muller-Steinhagen and Muddis (1989). For the present flow conditions and initial heat flux range of 20 to 40 kW/m^2, the asymptotic effectiveness ratio is in the range of 0.775 to 0.825. On the other hand, the asymptotic pressure drop ratio increases to a maximum value (at 30 kW/m^2) and then decreases again with the increase of initial heat flux. The asymptotic pressure drop ratio values are in the range of 1.25 to 1.35% for the same operating conditions. It is clear from these figures that the effect of initial heat flux (5% increase in □ □$_o$ □ and 10% extra pumping power) is small compared with the effect of flow average velocity (15% and 35% respectively) and bulk particle concentration (12.5% and 50% respectively).

SUMMARY AND CONCLOSSIONS:

The available fouling experimental data are first assessed and analyzed. These data are then used to develop a semi-empirical model for particulate fouling in plate type heat exchangers. Expressions of the asymptotic fouling resistance and time constant are obtained. One expression for fouling is in terms of flow average velocity alone. The other is in terms of bulk particle concentration alone while the third is in terms of the initial heat flux alone. Three similar expressions are developed for the time constant. A general expression for fouling resistance is obtained using the developed correlations and the used experimental data in terms of flow average velocity, bulk particle concentration and initial heat flux. A similar expression is also obtained for the time constant. The developed model is used to predict the effect of fouling on the heat exchanger design, operation and performance parameters. This model can be used as a quick and cheap tool to predict the fouling effects on heat exchangers and also leads to a better understanding of this important phenomenon.

The present results showed that both the fouling rate at the beginning of operation after cleaning and the asymptotic fouling resistance increase as the flow average velocity decreases or as the bulk particle concentration increases. As well, the rate of fouling decreases as the operation time increases for constant flow average velocity or bulk particle concentration. The present predictions and experimental data show that the effect of initial heat flux on fouling resistance is small compared with that of average velocity or bulk particle concentration. Moreover, the present predictions show good agreement with the experimental data of plate type and double pipe heat exchangers. The present results for exchanger effectiveness decreases with time at the beginning of operation since previous cleaning while the pressure drop increases for constant flow average velocity or bulk particle concentration or initial heat flux.

The asymptotic effectiveness ratio decreases as the flow average velocity decreases or as the bulk particle concentration increases. On the other hand, the asymptotic pressure drop ratio decreases as the flow average velocity decreases or as the bulk particle concentration increases. The predicted results show a decrease in the exchanger effectiveness in the range of 11% to 32.5% compared with the data of clean fluids under the considered operating conditions. As well, the present results show an increase in pressure drop in the range of 15% to 75% over that needed for cleaned fluids for the same conditions. Therefore, an extra pumping power of 15 to 75% is need for the circulation system due to fouling and this adds an extra initial and operating costs to the pumping system. The predicted results suggest the use of the present model to document the design, operation and performance parameters of plate type, double pipe and similar heat exchangers.

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TABLE I: CONSTANTS OF FOULING RESISTANCE EXPRESSIONS

Constants \ Equation	(2)	(4)	(6)
a_o	1.376	0.304	$-2.663*10^{-2}$
a_1	-4.842	$-5.7*10^{-4}$	$1.47*10^{-2}$
a_2	4.667	$7.6*10^{-7}$	$-2.445*10^{-4}$

TABLE II: CONSTANTS OF TIME CONSTANT EXPRESSIONS.

Constants \ Equation	(3)	(5)	(7)
b_o	0.362	0.1085	1.054
b_1	-1.417	$-2.55*10^{-4}$	$-6.32*10^{-2}$
b_2	1.48	$1.77*10^{-7}$	0.001

TABLE III: CONSTANTS OF THE GENERAL EXPRESSIONS (8) & (9)

c_o	-8.867	e_o	0.692
c_1	-57.47	e_1	1.0
c_2	$1.28*10^{-4}$	e_2	0.0
c_3	1.0	e_3	5.587
c_4	-35.23	e_4	-64.75
c_5	97.8	e_5	-17.27
c_6	-270	e_6	92.1

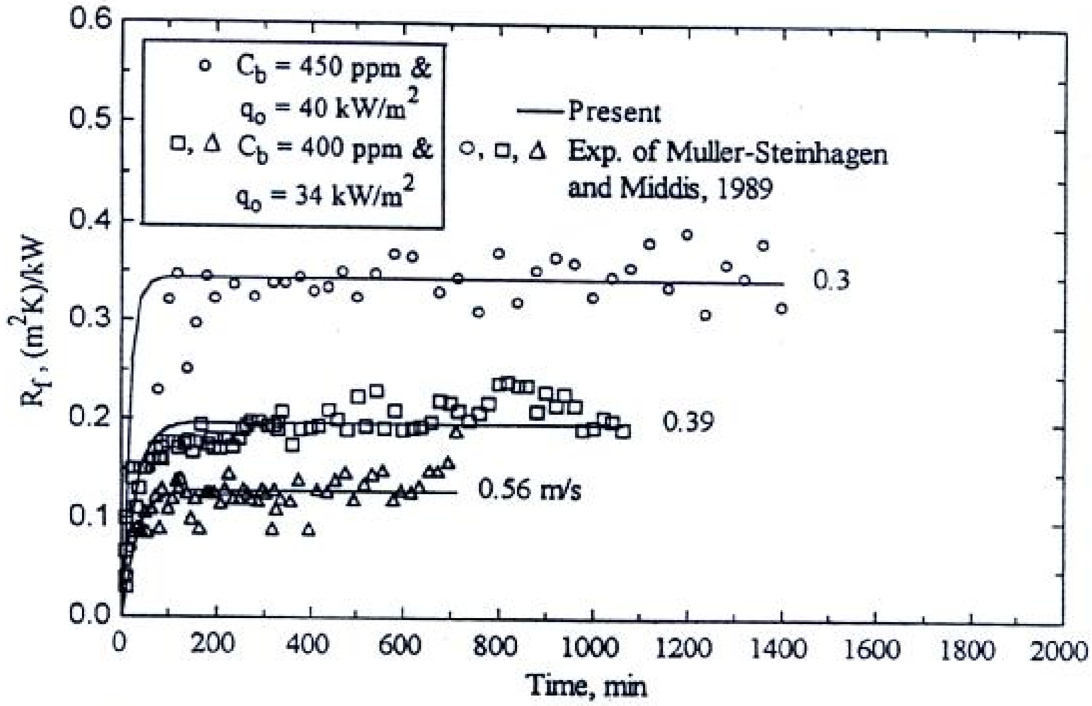

Fig. 1. Comparison of predictions with experimental data of plate heat exchanger.

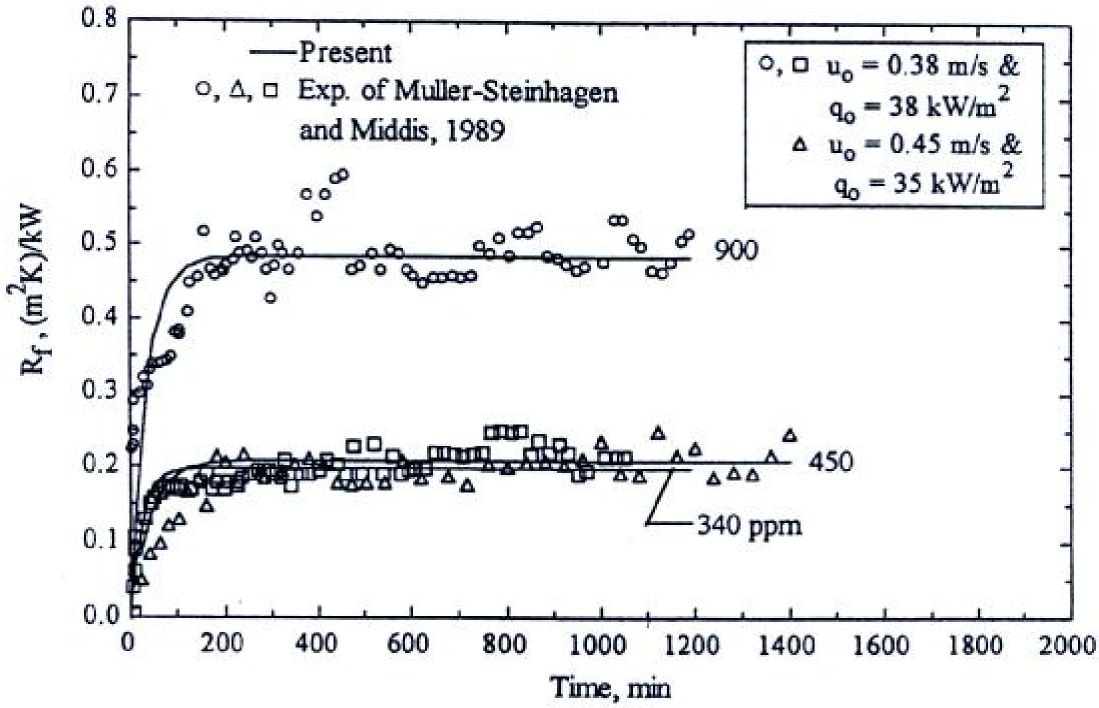

Fig. 2. Comparison of predictions with experimental data of plate heat exchanger.

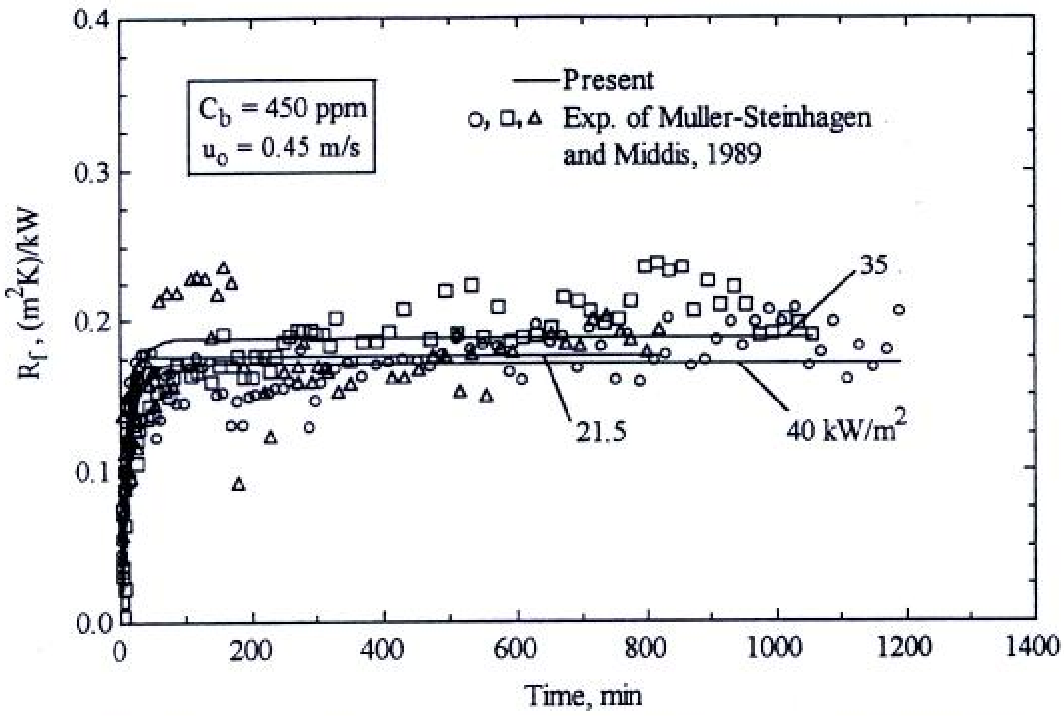

Fig.3. Comparison of predictions with experimental data of plate heat exchanger.

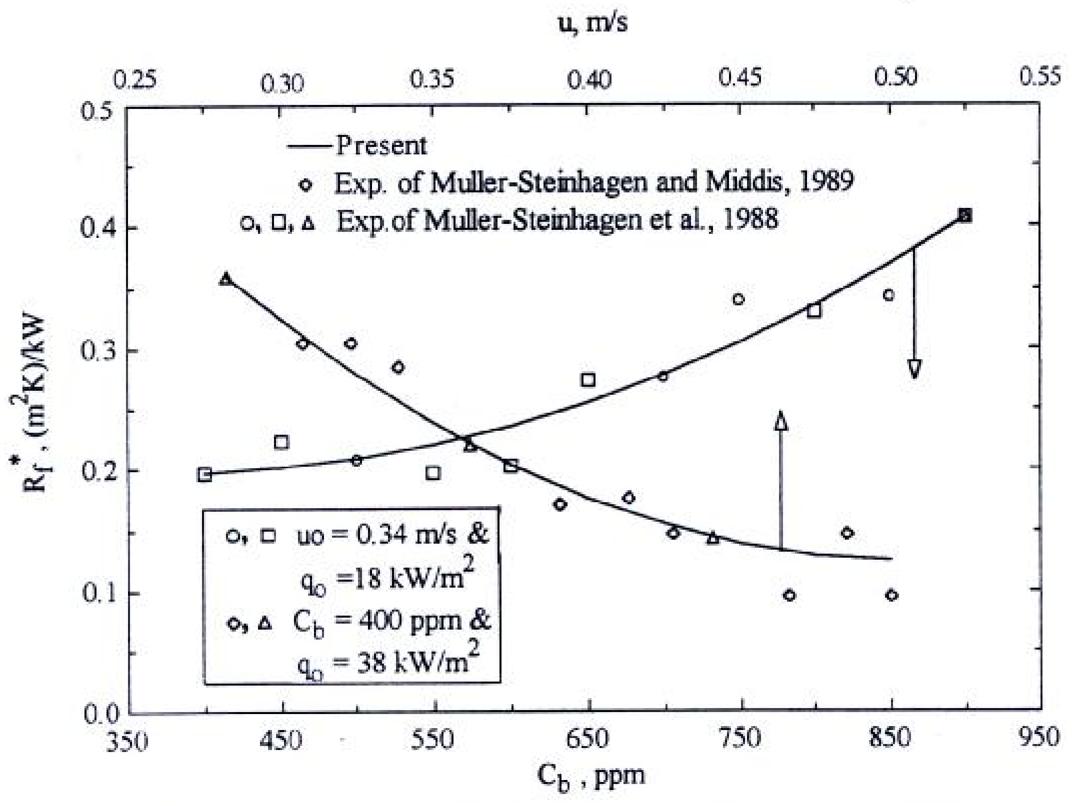

Fig.4. Comparison of predictions with experimental data of plate heat exchanger.

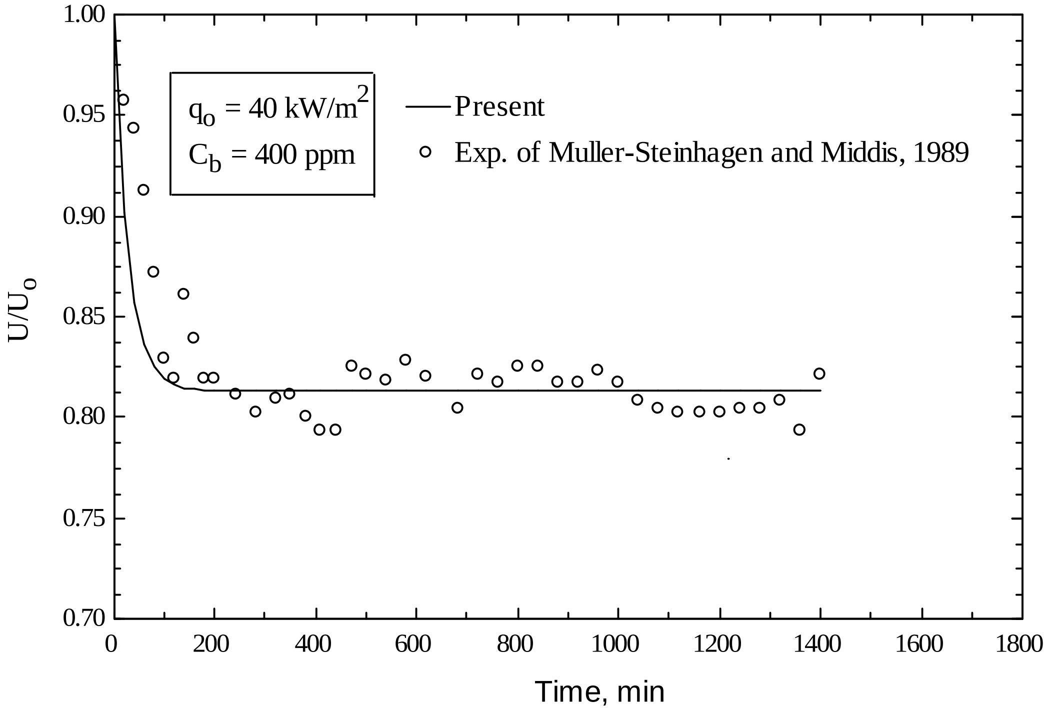

Fig.5. Comparison of predictions with experimental data of plate heat exchanger.

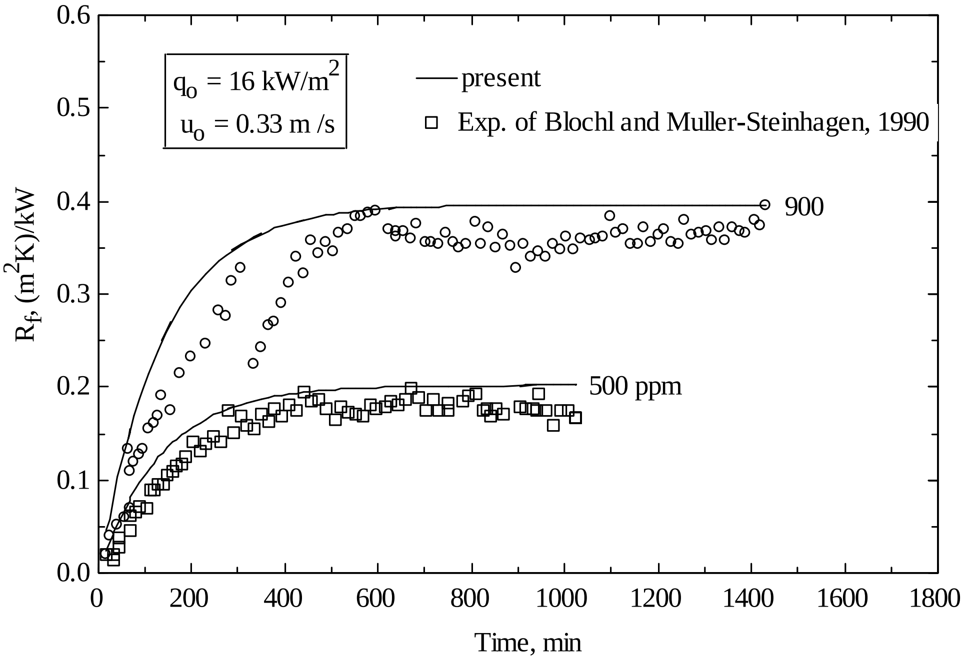

Fig. 6. Comparison of predictions with experimental data of double pipe heat exchanger.

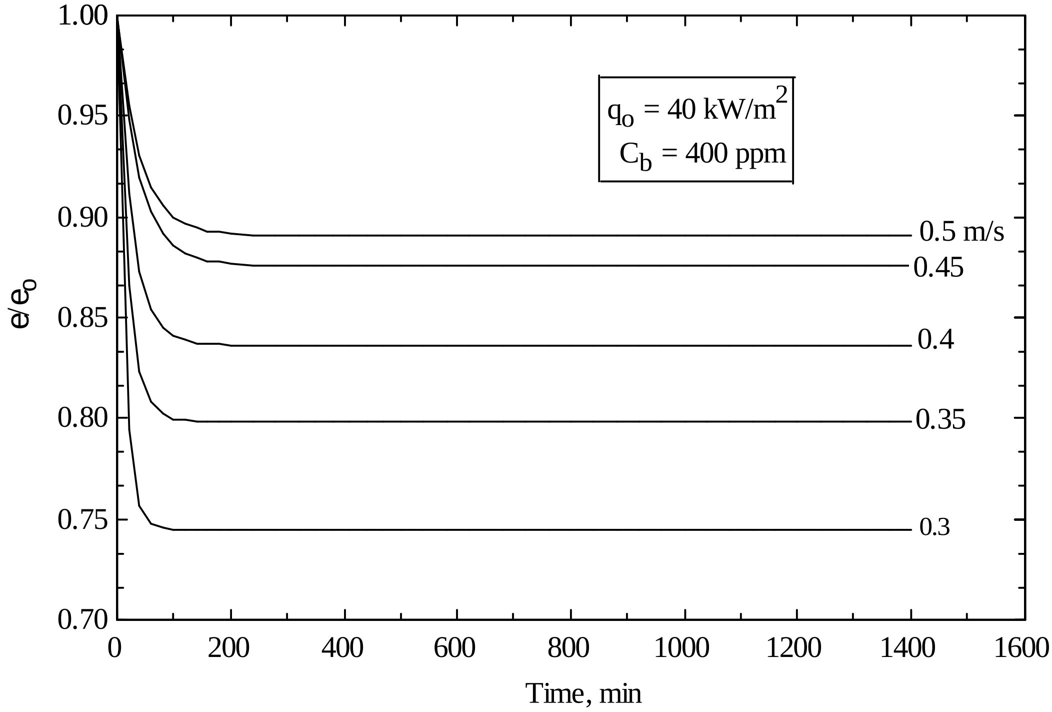

Fig.7. Variation of predicted exchanger effectiveness with time and flow velocity.

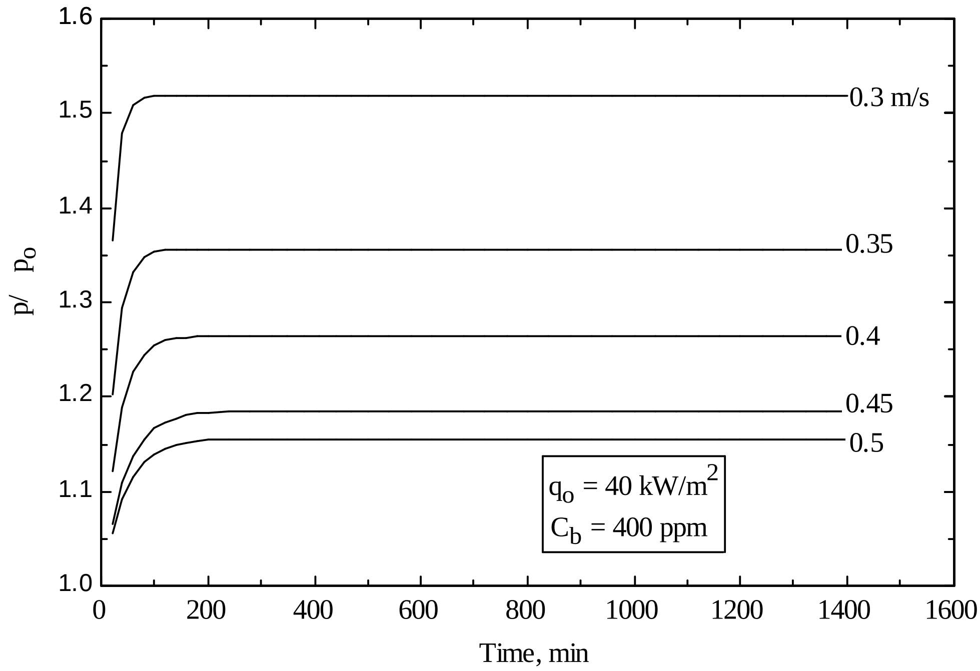

Fig. 8. Variation of predicted p/ p_o with time and flow velocity.

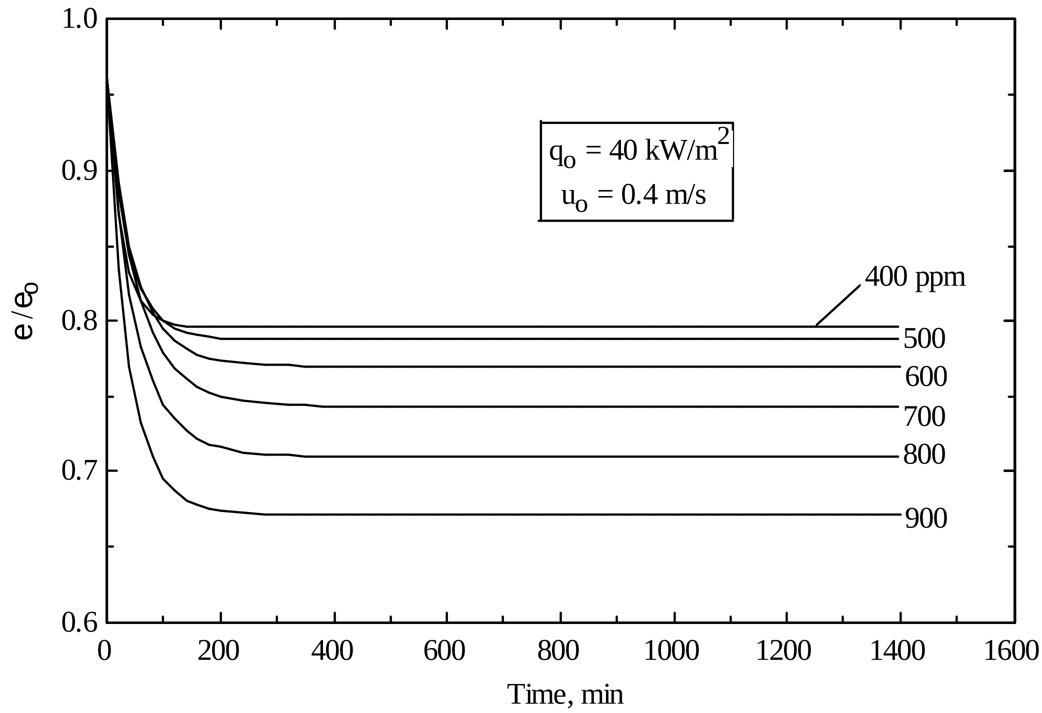

Fig. 9. Variation of predicted exchanger effectiveness with time and particle concentration.

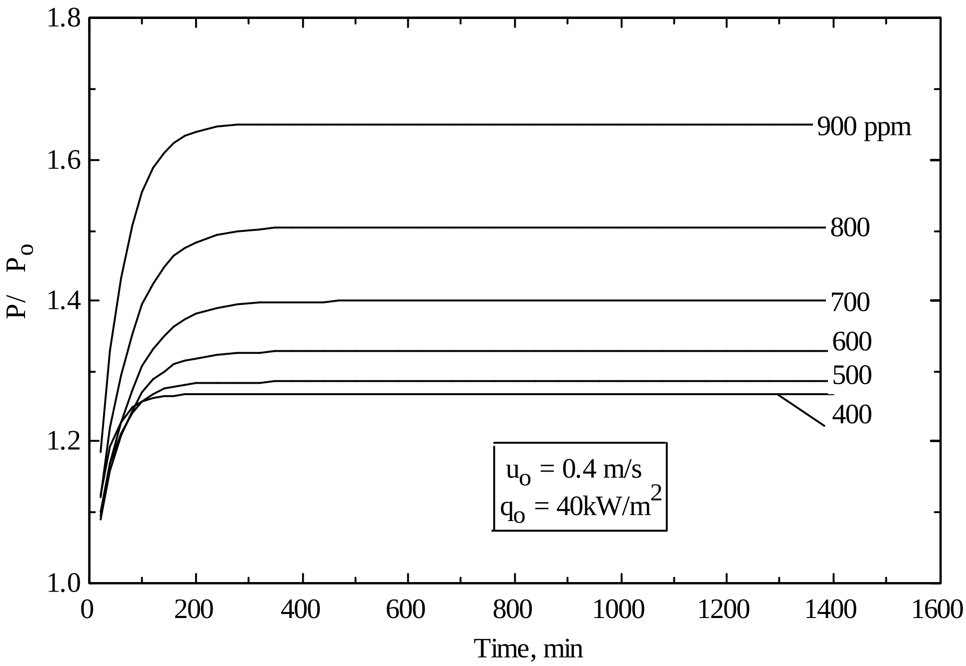

Fig.10. Variation of predicted p/ p_o with time and particle concentration.

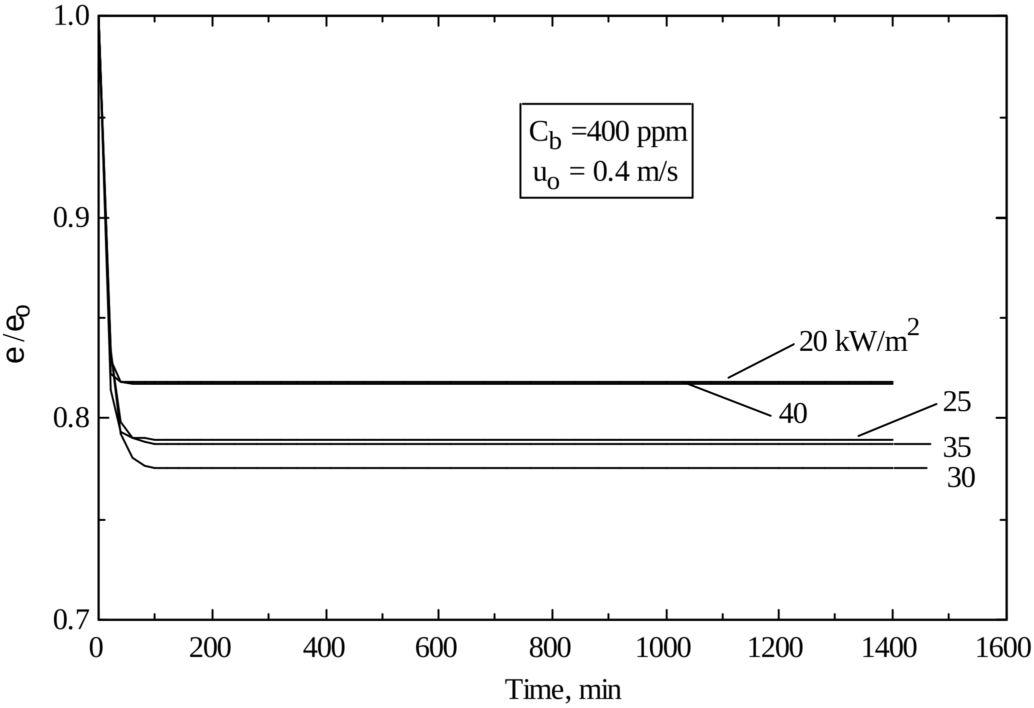

Fig. 11. Variation of predicted exchanger effectiveness with time and heat flux.

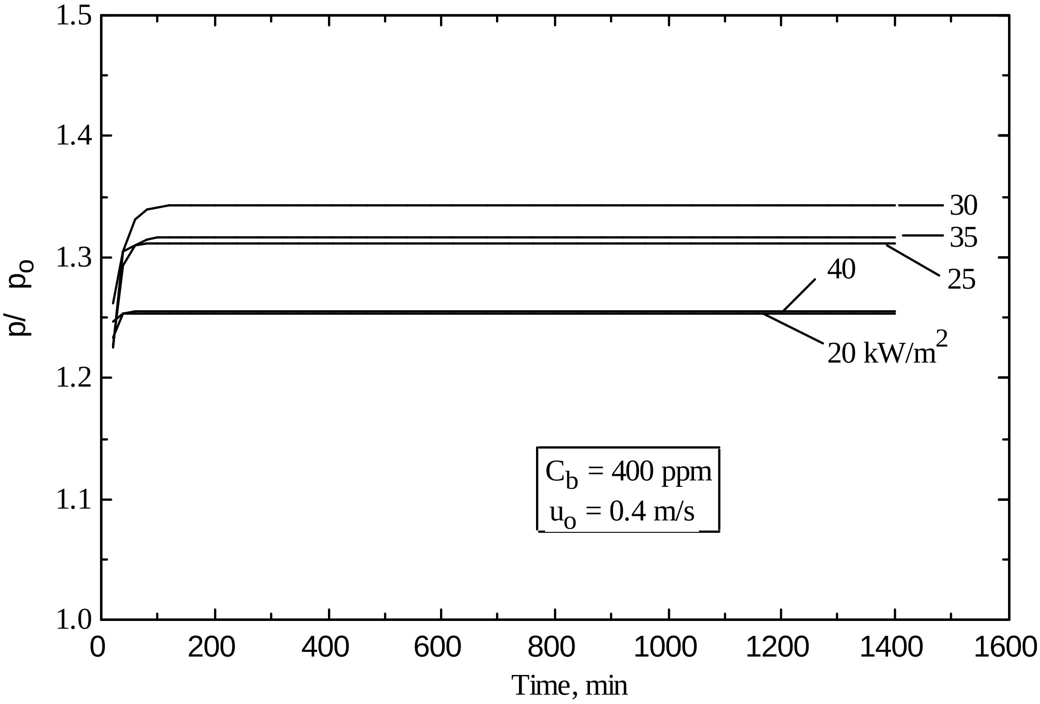

Fig. 12. Variation of predicted p/ p_o with time and heat flux.