INVESTIGATION OF HEAT TRANSFER CONDITIONS IN SCRAPED SURFACE HEAT EXCHANGER

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Abstract

Scraped surface heat exchangers are widely used in the food industry and in the developing aseptic technology to guarantee products of high quality. In the literature review the flow and heat transfer conditions of these heat exchangers are analysed. An experimental station supplied with data acquisition system has been built, which makes possible to vary testing parameters. Heat transfer equations required for dimensioning scraped surface heat exchangers were determined at different operational parameters.

Keywords: scraped surface heat exchanger, heat transfer, dimensionless equation.

Introduction

In the food industry heat treatment equipment have more and more importance, which sterilize products of different viscosity preserving their taste, flavour, colour and substance, and also meet requirements of aseptic technology. Scraped surface heat exchangers which work efficiently in a number of Hungarian food-industrial plants suit these conditions. In this type of heat exchangers scraping blades prevent material from burning on the wall under short-time intensive heat treatment. These blades are fixed to the rotating shaft, can be fitted in some rows, their form and way of tightening can be varied. Quick spread of these heat exchangers forces the analysing study of heat transfer conditions in them.

Literature Review

The literature has been reviewed making use of article [1] (CUEVAS et al. 1982) among others.

C. W. VOGT constructed the first scraped surface heat exchanger and registered its patent in 1928. Scraped surface heat exchangers have been applied for high temperature — short time sterilization since 1946. The first experimental heat exchanger plant was built in 1947 in Maywood.

Experiments were going on for two years:

- methods were developed for sterilization of the equipment;
- influence of economical and practical parameters on choosing material pressure and heat transfer wall temperature was analysed;
- the optimum mass flow rate in the heat exchanger was specified.

Between 1949-52 different foodstuffs, dairy, meat, vegetable products and acid foods were produced on the complete aseptic cannery line, built on the experimental plant of Votator. Heat treatment of materials containing no discrete particles could be successfully carried out. Serial production of the equipment and adoption of the procedure started between 1948 and 1950 in the USA.

The heat transfer phenomena in scraped surface heat exchanger have been studied by many authors.

Cuevas with his colleagues in 1980 and Cuevas-Garcia in 1981 carried out measurement series for observing changes of material temperature leaving the heat exchanger as a function of the rotational speed of the blades and the mass flow rate. In the experiments the outlet temperature of the materials to be heated (water, soy bean extract) was defined as the depending variable. Two important facts are evident from these studies: the effect of blade rotation is more significant at low blade speeds, where outlet temperature increases sharply as rotations per minute are increased, whereas this effect is negligible or even negative at higher values of rpm; and higher outlet temperatures correspond to lower mass flow rates. For a given steam pressure and product inlet temperature, the system response is more sensitive to the effect of scraping at higher flow rates, which illustrates the interaction between both variables.

Different measurements were carried out with water to determine overall heat transfer coefficient in scraped surface heat exchanger (HOULTON, 1944; GHOSAL, 1967; BOLANOWSKI, 1967). The heat transfer phenomenon in scraped surface heat exchanger has been commonly analysed assuming that axial velocity effects (i.e. mass flow rate effects) are negligible (TROMMELEN, 1971; KOOL, 1958; HARRIOT, 1959), as developed in the Penetration Theory. In contradiction to this, Couves-Garcia in 1981 showed on the basis of variance analysis that the variables were in considerable interaction with each other. They determined that the overall heat transfer coefficient increases as a result of scraping, but only up to a certain point, and further increments in blade speed do not induce any significant improvement in heat transfer, and may even decrease the k (overall heat transfer coefficient) values of blades speed. The optimum point is at 350–400 revolutions per minute. The reason of this phenomenon has not been totally cleared up yet. It is just possible, especially in units with relatively small diameters, that some of the material scraped away from the wall may be thrown back against the wall due to high centrifugal forces at high blade speeds, thus lowering the overall heat transfer coefficient value (KOOL, 1958).

In calculations of overall heat transfer coefficient some scientists have assumed that backmixing phenomena are negligible (HOULTON, 1944; SKELLAND, 1958; SKELLAND et al., 1962; BLAISDELL and ZAHRADNIK, 1959). To control this assumption, measurements were carried out under conditions producing backmixing effects (minimum mass flow and maximum scraping speed) (CUEVAS et al. 1980; CUEVAS and GARCIA, 1981). The results indicated that, although a moderate amount of backmixing was apparent, the residence time distribution function more closely approximated plug flow behaviour than a completely mixed system.

Similar conclusions could be derived from other works, too (CHEN and ZAHRADNIK, 1961; PENNEY and BELL, 1969; TROMMELEN et al., 1971). Studies of special importance were carried out by BOTT and colleagues in 1968. They developed a theoretical model of the effect of backmixing on heat transfer in scraped surface heat exchanger. They concluded that backmixing effects could be ignored at low Stanton numbers and high Peclet numbers.

Previous attempts to model the scraped surface heat exchanger showed that classical methods such as the Penetration Theory were inadequate under the conditions studied here except for low mass flow rates. Instead dimension analysis was applied here since it is a powerful heat transfer methodology when no satisfactory theory exists (BIRD et al. 1960; MCCABE and SMITH, 1956). The dimensional correlations were derived by the Π theorem. No geometrical factors are determined in an explicit manner, since they were not included as independent variables in the experiments.

On the basis of studying heat transfer phenomena most authors found the following equation suitable to describe the inside heat transfer coefficient. This equation is created from dimensionless groups

$$Nu = A\, Re_A^B\, Re_R^C\, Pr^D \left(\frac{\mu}{\mu_W}\right)^E. \tag{1}$$

The dimensionless numbers:

$$Nu = \frac{\alpha_i (D_1 - D_2)}{\lambda}, \tag{2}$$

$$Re_A = \frac{(D_1 - D_2) v \rho}{\mu}, \tag{3}$$

$$Re_R = \frac{D_1^2 N \rho}{\mu}, \tag{4}$$

$$P_T = \frac{\mu c}{\lambda}. \tag{5}$$

Table 1

Data source	Exponents of the dimensionless model A	B	C	D	E	
1.a. Cuevas-Cheryan-	0.304	0.504	0.322	0.33	0.18	$Re < 1800$, water
1.b. Porter	$4.59 \cdot 10^{-4}$	0.942	0.637	0.33	0.18	$Re > 1800$, water
2. Sykora	0.565	−0.01	0.48	0.40	0	water glycerine
3.a. Skelland	3.26	0.57	0.17	0.47	0	low viscosity
3.b. Skelland	0.0306	1.0	0.062	0.7	0	high viscosity
4. Ramdas	57	0.059	0.113	0.063	−0.018	
5. Bott-Romero	0.013	0.46	0.6	0.87	0	
6.a. Maingonnat Corrieu	5.86	0.29	0.32	0.33	0	low viscosity 4 rows of blades
6.b.	3.1	0.4	0.36	0.33	0	2 rows of blades
6.c.	2.24	0.017	0.56	0.33	0	high viscosity 4 rows of blades
6.d.	2.04	0.16	0.52	0.33	0	2 rows of blades
7. Ghosal	0.123	0.79	0.65	0.6	0	
8. Uhl	0.036	0	0.66	0.33	0.18	
9. Penney-Bell	0.123	0	0.78	0.33	0.18	
10. Sykora	4.09	0	0.48	0.24	0	

Table 1 shows the constants of dimensionless correlations and the validity ranges of them which can be found in the literature. Studies of R. Cuevas and other authors show that, despite the vast differences in the order of magnitude between axial and rotational Reynolds numbers, Nusselt numbers are significantly effected by both variables.

According to the studies described above, the outlet temperature decreased as the mass flow rate was increased. This process may occur in two ways: either the effect of blade rotation will interact with the axial flow and trigger transition to turbulent flow at lower values of Re_A ; or exactly the opposite effect, namely, that the rotational velocity effects result in a dampening of the onset of turbulence in axial direction. In this particular case, the state of mixing generated due to the action of the blades would seem to favor the former type of situation. The heat transfer coefficient increases slower than the Reynolds numbers. This assumption is verified by the Reynolds numbers' exponents of *Table 1*. ($B < 1, D < 1$).

The exponents of the Prandtl number and viscosity factor are determined on the understanding that the flow in a scraped surface heat exchanger is a combination of pure tube flow and pure rotational flow. Some Prandtl number's exponents of *Table 1* contradict to this assumption ($D < 0.3$ in 4. and 10. rows, $D > 0.5$ in 3.b, 5. and 7. rows).

Experiments were carried out for studying heat transfer phenomena in scraped surface heat exchangers. Comparison is made with experiments and exponents of *Eq.* (1) listed in *Table 1*.

Experimental Procedure
Experimental Set-up

An educational and experimental station was established for studying thermic and flow processes of Newtonian and non-Newtonian materials of low and high viscosity and also for dynamic studies of scraped surface heat exchanger system. The set-up of the scraped surface heat exchanger is shown in *Fig. 1*.

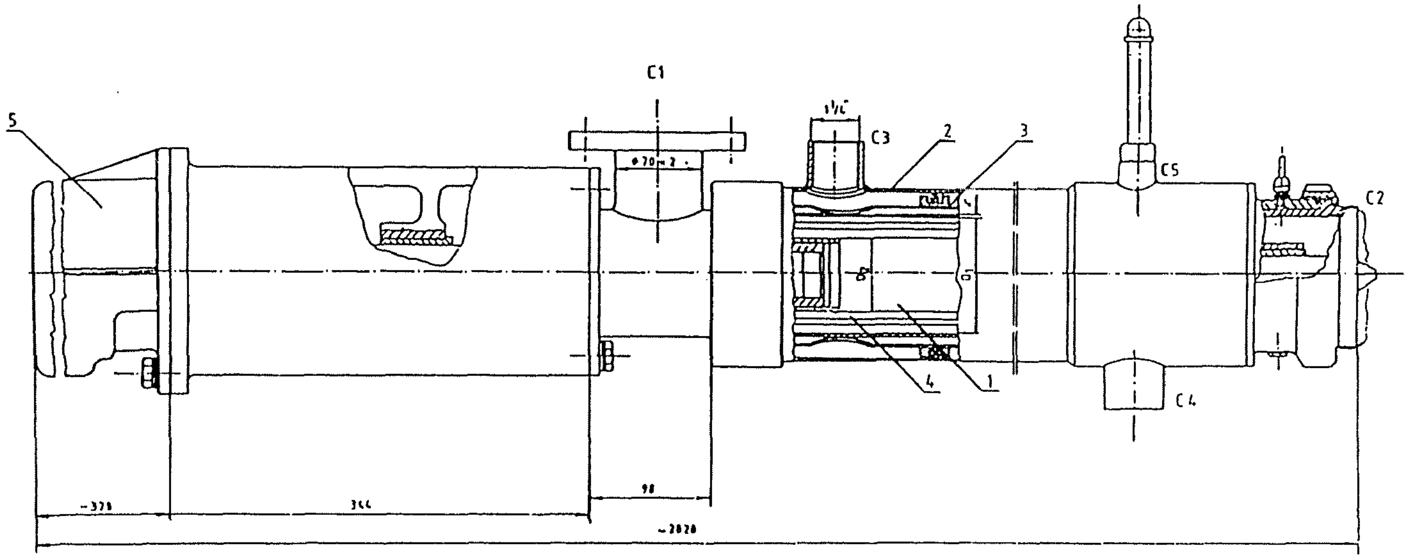
The unit is fitted with four rows of blades which are, as a result of rotation, centrifugally forced to the inner wall, mechanically induce turbulence, film removal and mix the product.

The scheme of the station with three scraped surface heat exchangers can be seen in *Fig. 2*. Working liquid is pumped from tank (1) by pump (2) to the heat exchangers. The pump has an infinitely variable gear, bypass allows recirculation to the tank as well as sampling. Heat treatment is carried out in sterilizer heat exchanger (3), recooling occurs in cooling heat exchangers (4) and (5). The heating medium is steam, the cooling medium is cold water. The recoolers can work in coflow or counterflow, in parallel or series connection.

It was necessary to work out a suitable system for measuring and analysing heat transfer processes, for determining temperature control strategies and operating parameters.

The on-line measuring of the following features makes possible to analyse steady-state and instationary thermal processes:

- working liquid: mass flow rate, temperature, pressure
- heating medium: mass flow rate, temperature, pressure
- cooling medium: mass flow rate, temperature
- rotor: rotational speed, electric power



C1	Material inlet	1	Shaft	$D_1 = 0.098$ m
C2	Material outlet	2	Outside tube	$D_2 = 0.06$ m
C3	Steam inlet	3	Inside tube	$\delta = 0.02$ m
C4	Condensate outlet	4	Blade	
C5	Thermometer	5	Motor	

Fig. 1.

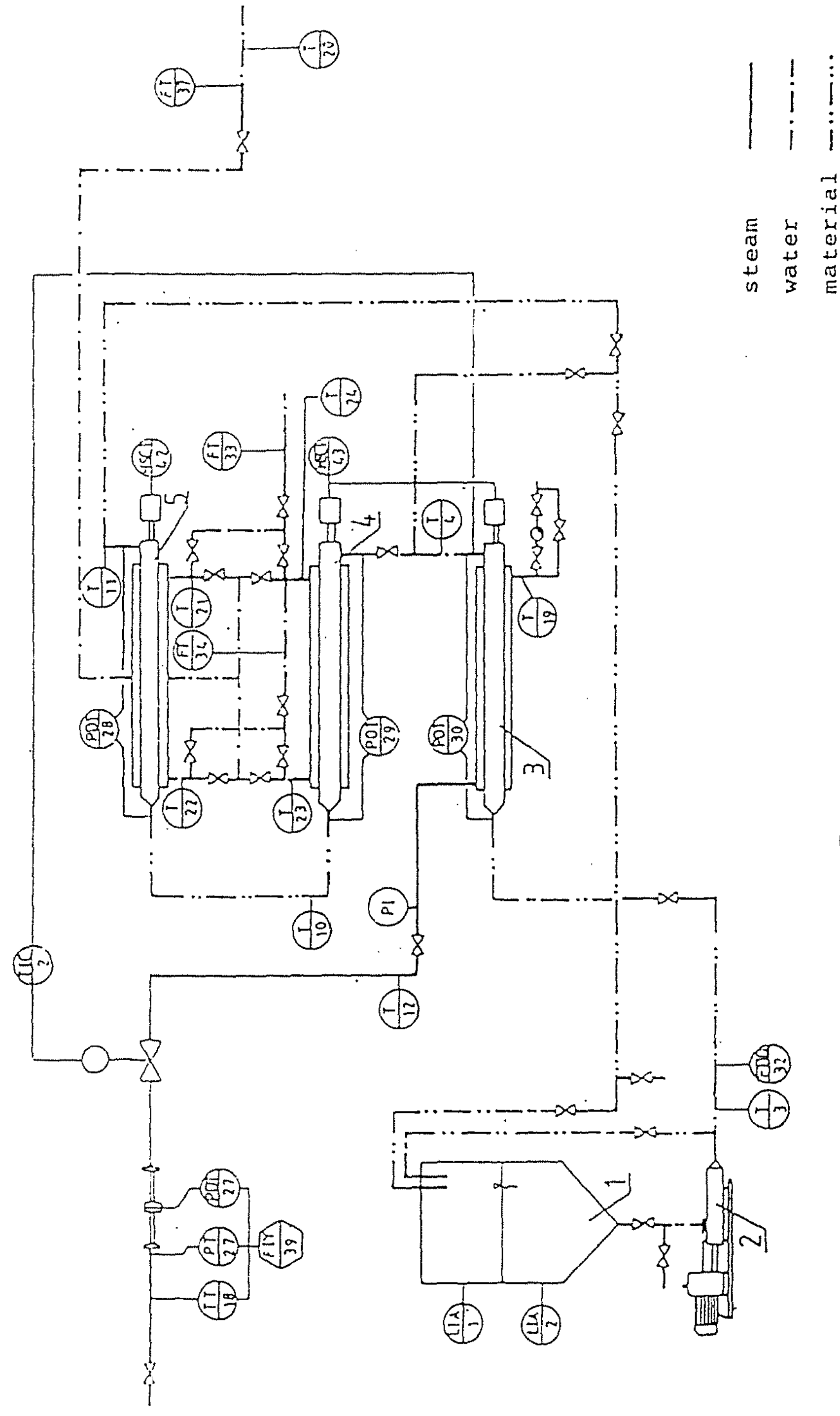


Fig. 2.

Fig. 2 shows the instrumentation of the station which solves measuring and control tasks by means of the following units:

- For temperature sensing: dual platinum resistance thermometer with protection of low time constant insuring the required measuring quality for panel meters, data acquisition and control.
- For measuring material flow rate: electromagnetic flowmeter has been built in because the working, heating and cooling media are electrically conductive liquids;
- For measuring the mass of the steam: a pipe with standard reducing pieces has been built in, in knowledge of the pressure drop on the pipe piece, the steam temperature and pressure and the geometric data, a microprocessor unit computes the value of steam mass flow in kg/hour in accordance with the standard;
- For sensing the pressure difference on the scraped surface heat exchangers: diaphragm transmitters were applied;
- Electrical speedometers are built in for controlling the motor speed of the scraped surface heat exchanger;
- Temperature controllers;
- The motor of the pump is protected against discharging and overcharging of the tank by locking;
- Frequency changer permits to infinitely vary the motor speed;
- The electric energy consumption of the motors is measured by power telemeters.

Data appear as resistance and voltage values on the instrument panel. The on-line measuring programs can be arranged according to the measuring tasks. The data acquisition system is connected with an IBM personal computer making evaluation of measurement data efficient.

Measurements

Experiments were carried out with different

- working liquids: water, tomato puree, yoghourt
- mass flow rates: $m = 500 - 2500$ kg/h
- rotational speeds: $N = 50 - 300$ rpm,
- heat treatment liquids: steam, water.

Using the temperature and mass flow rate values measured in the scraped surface heat exchanger units, the heat flow can be calculated. From the average values of the heat flow from inside to outside and from outside to inside, the overall heat transfer coefficient can be determined. Knowing the steam-side (outside) heat transfer coefficient (for condensation), the scraped-side (inside) heat transfer coefficient is as follows:

$$\alpha_i = \frac{1}{\frac{1}{k} - \frac{1}{\alpha_0 \frac{F_0}{F_i}} - \frac{F_i}{F_m} \sum \frac{\delta}{\lambda}} \quad (6)$$

The measurement results and the calculated values are shown in *Tables 2* and *3.*

In order to compare our results with those of other authors, we evaluated the measurement data in the form of the following dimensionless equation:

$$Nu = A\, Re_A^B\, Re_R^C\, Pr^D \left(\frac{\mu}{\mu_W}\right)^E \quad (1)$$

Exponents of *Eq.* (1) have been determined as follows:

Exponents of the Prandtl number and geometric factor $D = 0.33$ $E = 0.18$ can be assumed on the basis of the above considerations.

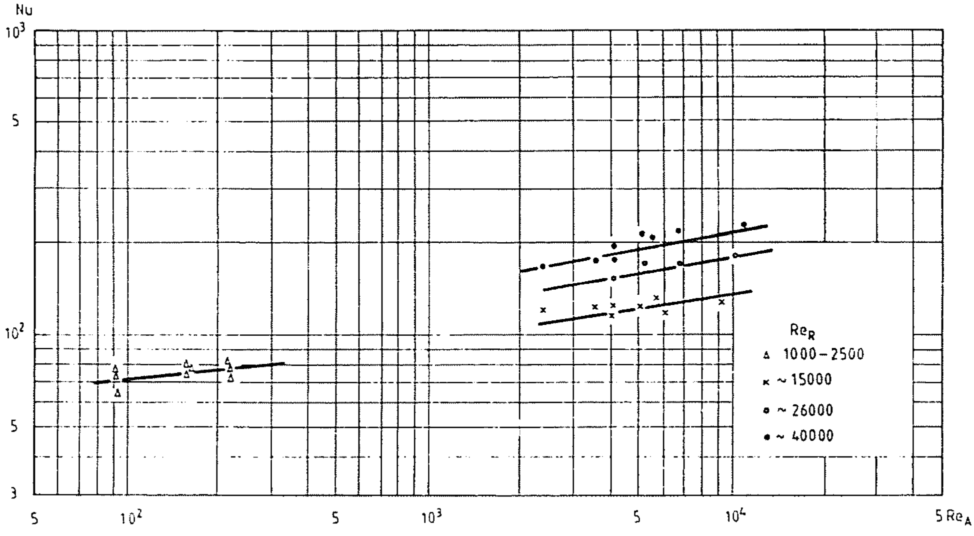


Fig. 3. Test results

The Nusselt number involving the inside heat transfer coefficient can be seen in *Figs 3* and *4* as a function of axial and rotational Reynolds numbers. Assuming that the measurement data are on parallel straight lines in *Fig. 4*

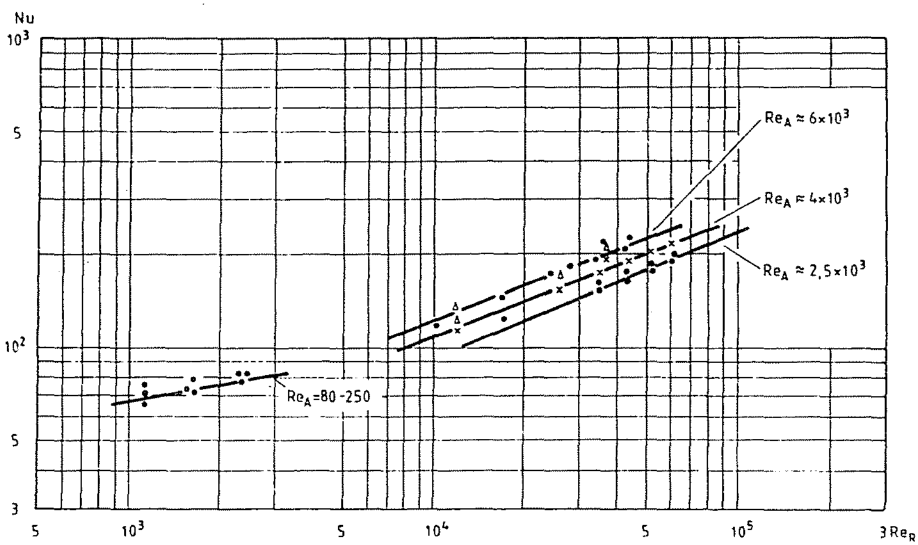


Fig. 4. Test results

– where the constant axial Reynolds numbers are indicated as parameters
– their average slopes are using the minimum square regression:

$C = 0.18$	if	$Re_A = 80 \div 250$	and	$Re_R = 1000 \div 2500$
$C = 0.4$	if	$Re_A = 2 \cdot 10^3 \div 10^4$	and	$Re_R = 10^4 \div 10^5$

In order to determine A and B exponents, *Eq.* (1) can be transformed into the following form:

$$Y = \frac{Nu}{Re_R^C Pr^D \left(\frac{\mu}{\mu_w}\right)^E} = A Re_A^B. \tag{7}$$

In *Fig. 5* the Y values can be seen as the function of Re_A number values. The exponents are:

$A = 3.00,\ B = 0.13$	if	$Re_A + 80 \div 250$	and	$Re_R = 1000 \div 2500$
$A = 0.523,\ B = 0.152$	if	$Re_A = 2 \cdot 10^3 \div 10^4$	and	$Re_R = 10^4 \div 10^5$

The dimensionless correlations determining the inside heat transfer coefficient in the heat exchanger are in the studied ranges as follows:

$$Nu = 3.00 \cdot Re_A^{0.13} Re_R^{0.18} Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.18}, \tag{8}$$

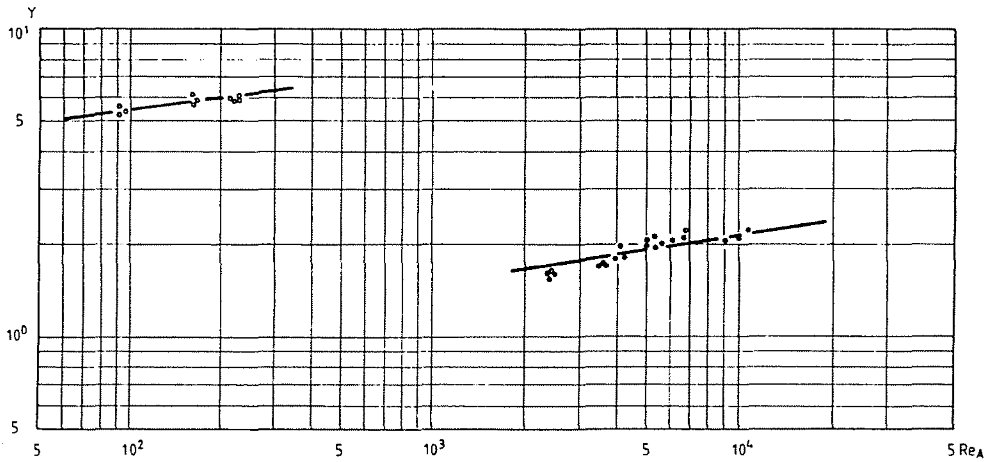


Fig. 5. Evaluation of test results

$$Re_A = 80 \div 250, \qquad Re_R = 1000 \div 2500,$$

$$Nu = 0.523 Re_A^{0.152} Re_R^{0.4} Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.18}, \tag{9}$$

$$Re_A = 2 \cdot 10^3 \div 10^4, \qquad Re_R = 10^4 \div 10^5.$$

The results of experimental studies carried out on scraped surface heat exchanger units can be compared with the dimensionless correlations of *Table 1*. *Fig. 6* shows the Nusselt number as a function of axial Reynolds number (Re_A), while *Fig. 7* demonstrates the Nusselt number as a function of rotational Reynolds number (Re_R).

It can be stated that correlations available in the literature show a wide dispersion. Our result correlation is between the values of *Table 1* in the studied ranges.

Studies have to be continued to describe heat transfer phenomena more exactly, taking effects of other factors into consideration.

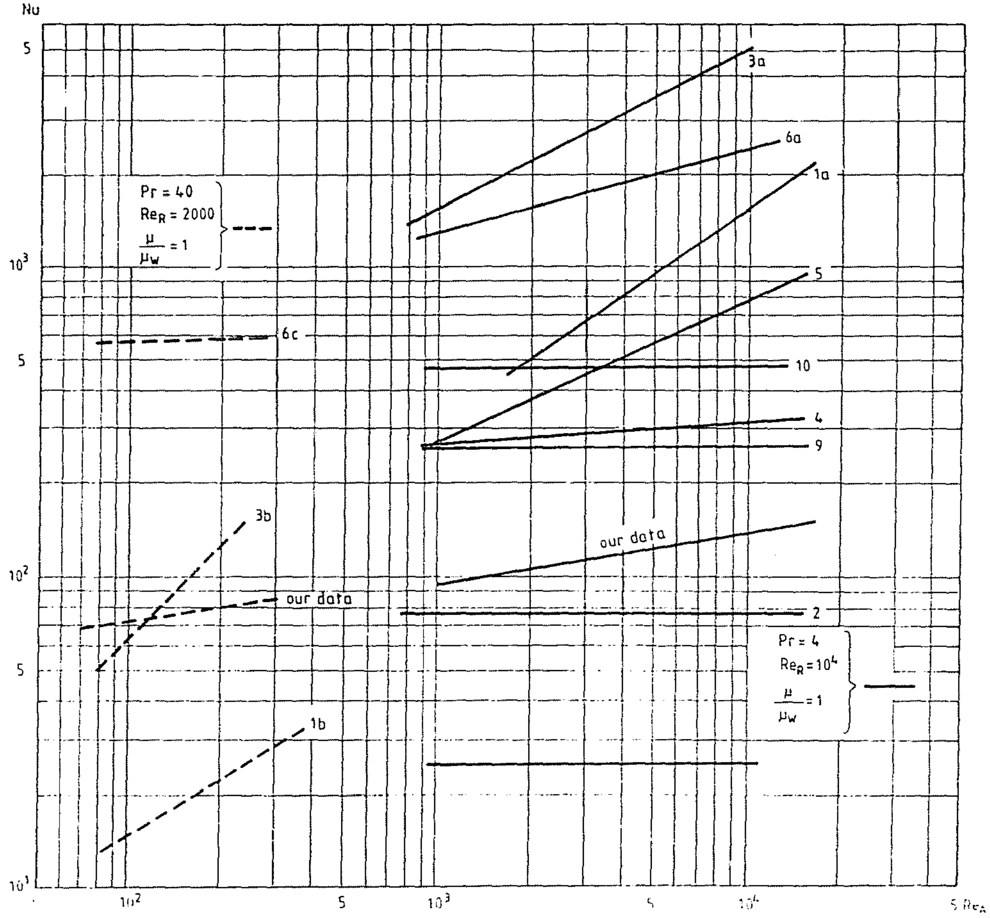


Fig. 6. Comparison with literature results

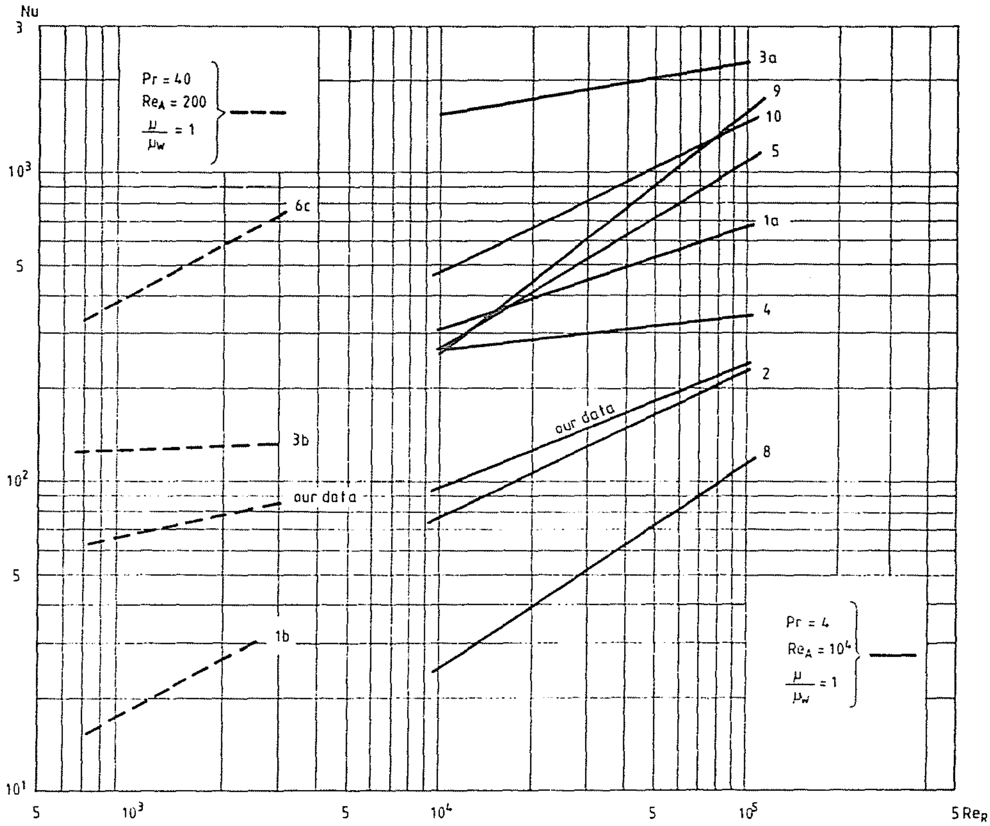


Fig. 7. Comparison with literature results

Table 2

No.	ma kg/s	N rpm	Q kw	k W/m^{2}K	alfain W/m^{2}K	Nu	material	heating medium
1	2.86E-01	4.20E+01	6.11E+01	1.33E+03	1.94E+03	1.15E+02	water	steam
2	2.79E-01	9.20E+01	6.89E+01	1.63E+03	2.65E+03	1.57E+02	water	steam
3	2.86E-01	1.30E+02	7.49E+01	1.83E+03	3.22E+03	1.91E+02	water	steam
4	3.66E-01	4.20E+01	6.29E+01	1.38E+03	2.04E+03	1.21E+02	water	steam
5	3.66E-01	9.20E+01	7.41E+01	1.74E+03	2.95E+03	1.75E+02	water	steam
6	3.66E-01	1.30E+02	8.16E+01	1.94E+03	3.57E+03	2.12E+02	water	steam
7	5.10E-01	4.20E+01	6.44E+01	1.35E+03	1.99E+03	1.18E+02	water	steam
8	5.19E-01	9.20E+01	8.04E+01	1.71E+03	2.88E+03	1.71E+02	water	steam
9	5.22E-01	1.30E+02	8.93E+01	1.96E+03	3.65E+03	2.17E+02	water	steam
10	6.63E-01	4.20E+01	7.15E+01	1.43E+03	2.16E+03	1.28E+02	water	steam
11	6.63E-01	9.20E+01	8.49E+01	1.78E+03	3.06E+03	1.82E+02	water	steam
12	6.66E-01	1.30E+02	9.29E+01	2.02E+03	3.85E+03	2.28E+02	water	steam
13	1.33E-01	6.00E+01	4.65E+01	1.38E+03	2.05E+03	1.20E+02	water	steam
14	1.33E-01	1.20E+02	4.88E+01	1.61E+03	2.62E+03	1.53E+02	water	steam
15	1.33E-01	1.50E+02	4.93E+01	1.70E+03	2.88E+03	1.68E+02	water	steam
16	1.33E-01	1.80E+02	4.85E+01	1.73E+03	2.97E+03	1.74E+02	water	steam
17	1.33E-01	2.10E+02	5.12E+01	1.83E+03	3.28E+03	1.92E+02	water	steam
18	1.90E-01	6.00E+01	4.72E+01	1.41E+03	2.14E+03	1.25E+02	water	steam
19	1.90E-01	1.20E+02	5.43E+01	1.67E+03	2.81E+03	1.64E+02	water	steam
20	1.90E-01	1.50E+02	5.41E+01	1.72E+03	2.96E+03	1.73E+02	water	steam
21	1.90E-01	1.80E+02	5.50E+01	1.81E+03	3.22E+03	1.89E+02	water	steam
22	1.90E-01	2.10E+02	5.75E+01	1.88E+03	3.48E+03	2.04E+02	water	steam
23	2.30E-01	6.00E+01	5.52E+01	1.42E+03	2.17E+03	1.27E+02	water	steam
24	2.30E-01	1.20E+02	6.00E+01	1.69E+03	2.91E+03	1.70E+02	water	steam
25	2.30E-01	1.50E+02	6.00E+01	1.74E+03	3.05E+03	1.78E+02	water	steam
26	2.30E-01	1.80E+02	6.38E+01	1.86E+03	3.48E+03	2.04E+02	water	steam
27	2.30E-01	2.10E+02	6.40E+01	1.92E+03	3.70E+03	2.16E+02	water	steam
28	3.00E-01	6.00E+01	6.83E+01	1.47E+03	2.35E+03	1.37E+02	water	steam
29	3.00E-01	1.20E+02	7.12E+01	1.76E+03	3.19E+03	1.87E+02	water	steam
30	3.00E-01	1.50E+02	7.35E+01	1.87E+03	3.59E+03	2.10E+02	water	steam
31	2.30E-01	1.40E+02	2.47E+01	7.19E+02	8.66E+02	6.58E+01	tomato	steam
32	2.30E-01	3.00E+02	2.50E+01	8.69E+02	1.09E+03	8.31E+01	tomato	steam
33	2.30E-01	2.00E+02	2.64E+01	7.92E+02	9.74E+02	7.40E+01	tomato	steam
34	2.30E-01	3.00E+02	2.72E+01	8.34E+02	1.04E+03	7.89E+01	tomato	steam
35	4.16E-01	1.40E+02	3.16E+01	8.06E+02	9.95E+02	7.56E+01	yogurt	steam
36	4.16E-01	2.00E+02	3.08E+01	8.34E+02	1.04E+03	7.89E+01	yogurt	steam
37	4.16E-01	3.00E+02	3.00E+01	8.43E+02	1.05E+03	8.00E+01	yogurt	steam
38	5.60E-01	1.40E+02	3.21E+01	7.75E+02	9.48E+02	7.21E+01	yogurt	steam
39	5.60E-01	2.00E+02	3.31E+01	8.21E+02	1.02E+03	7.74E+01	yogurt	steam
40	5.60E-01	3.00E+02	3.42E+01	8.69E+02	1.09E+03	8.31E+01	yogurt	steam

Table 3

No.	Nu	Re_A	Re_R	Y	Nucal.	Error %
1	1.15E+02	4.11E+03	1.20E+04	1.88E+00	1.14E+02	1.55E+00
2	1.57E+02	4.01E+03	2.62E+04	1.87E+00	1.55E+02	1.63E+00
3	1.91E+02	4.11E+03	3.70E+04	1.98E+00	1.79E+02	7.13E+00
4	1.21E+02	5.26E+03	1.20E+04	1.97E+00	1.18E+02	2.73E+00
5	1.75E+02	5.26E+03	2.62E+04	2.08E+00	1.61E+02	8.52E+00
6	2.12E+02	5.26E+03	3.70E+04	2.19E+00	1.85E+02	1.42E+00
7	1.18E+02	6.22E+03	1.01E+04	2.06E+00	1.13E+02	4.38E+00
8	1.71E+02	6.85E+03	2.41E+04	2.10E+00	1.63E+02	4.91E+00
9	2.17E+02	6.85E+03	3.71E+04	2.25E+00	1.93E+02	1.24E+01
10	1.28E+02	9.48E+03	1.20E+04	2.08E+00	1.29E+02	−8.1E−01
11	1.82E+02	1.03E+04	2.85E+04	2.09E+00	1.85E+02	−1.6E+00
12	2.28E+02	1.11E+04	4.34E+04	2.22E+00	2.21E+02	3.01E+00
13	1.20E+02	2.45E+03	1.73E+04	1.68E+00	1.22E+02	−1.4E+00
14	1.53E+02	2.45E+03	3.46E+04	1.63E+00	1.61E+02	−4.7E+00
15	1.68E+02	2.45E+03	4.33E+04	1.63E+00	1.76E+02	−4.3E+00
16	1.74E+02	2.45E+03	5.19E+04	1.57E+00	1.89E+02	−7.9E+00
17	1.92E+02	2.45E+03	6.06E+04	1.63E+00	2.01E+02	−4.4E+00
18	1.25E+02	3.62E+03	1.73E+04	1.75E+00	1.29E+02	−3.2E+00
19	1.64E+02	3.62E+03	3.46E+04	1.74E+00	1.70E+02	−3.8E+00
20	1.73E+02	3.62E+03	4.33E+04	1.68E+00	1.86E+02	−7.2E+00
21	1.89E+02	3.62E+03	5.19E+04	1.71E+00	2.00E+02	−5.7E+00
22	2.04E+02	3.62E+03	6.06E+04	1.74E+00	2.13E+02	−4.3E+00
23	1.27E+02	4.23E+03	1.73E+04	1.78E+00	1.32E+02	−4.0E+00
24	1.70E+02	4.23E+03	3.46E+04	1.81E+00	1.75E+02	−2.6E+00
25	1.78E+02	4.23E+03	4.33E+04	1.73E+00	1.91E+02	−6.7E+00
26	2.04E+02	4.23E+03	5.19E+04	1.85E+00	2.05E+02	−6.1E−01
27	2.16E+02	4.23E+03	6.06E+04	1.84E+00	2.18E+02	−1.1E+00
28	1.37E+02	5.65E+03	1.73E+04	1.92E+00	1.38E+02	−9.0E−01
29	1.87E+02	5.65E+03	3.46E+04	1.99E+00	1.82E+02	2.51E+00
30	2.10E+02	5.65E+03	4.33E+04	2.04E+00	1.99E+02	5.29E+00
31	6.58E+01	9.40E+03	1.12E+03	5.37E+00	6.68E+01	−1.4E+00
32	8.31E+01	2.26E+02	2.40E+03	5.92E+00	8.58E+01	−3.2E+00
33	7.40E+01	9.40E+01	1.60E+03	5.67E+00	7.12E+01	3.96E+00
34	7.89E+01	9.40E+01	2.40E+03	5.62E+00	7.66E+01	3.04E+00
35	7.56E+01	1.68E+02	1.12E+03	6.17E+00	7.20E+01	5.02E+00
36	7.89E+01	1.68E+02	1.60E+03	6.04E+00	7.68E+01	2.78E+00
37	8.00E+01	1.68E+02	2.40E+03	5.70E+00	8.26E+01	−3.1E+00
38	7.21E+01	2.26E+02	1.12E+03	5.89E+00	7.48E+01	−3.6E+00
39	7.74E+01	2.26E+02	1.60E+03	5.93E+00	7.98E+01	−3.0E+00
40	8.31E+01	2.26E+02	2.40E+03	5.92E+00	8.58E+01	−3.2E+00

Summary

Using the experimental studies, a dimensionless correlation was determined for calculating the internal scraped-side heat transfer coefficient which allows to determine the heat transfer surface for heat treatment or sterilizing.

Nomenclature

A	exponent
B	exponent
c	specific heat
C	exponent
D	exponent
D_1	tube diameter
D_2	shaft diameter
F_i	inside area for heat transfer
F_0	outside area for heat transfer
F_m	mean area for heat transfer
k	overall heat transfer coefficient
N	blade speed, revolutions per minute
Nu	Nusselt number
$\dot{m}$	mass flow
Pr	Prandtl number
Q	heat flow
Re_A	axial Reynolds number
Re_R	rotational Reynolds number
v	mass flow speed
Y	factor in *Eq.* (7)
α_i	inside (scraped-side) heat transfer coefficient
α_0	outside (steam-side) heat transfer coefficient
δ	wall thickness
λ	thermal conductivity
μ	viscosity
μ_w	viscosity at wall temperature
ρ	density

References

1. Cuevas, R. – Cherian, M. – Portier, V. L.: Performance of a Scraped-Surface Heat Exchanger Under Ultra High Temperature Conditions: A Dimensional Analysis. *Journal of Food Science* 1982. Vol 47. pp. 619-641.