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Self-Regulated Thermal Process and Cooling Properties of Quenchants

NIKOLAI KOBASKO, VOLODYMYR DOBRIVECHER
Intensive Technologies Ltd.,
Blwr Wernadskoho 63, off.71, Kyiv, 03142
UKRAINE
nikobasko@aol.com, dobrivecher@yahoo.com, www.itl.kiev.ua

Abstract: - This paper presents the analysis of heat transfer regularities for self-regulated thermal process. The self-regulated thermal process is a process during which there is no film boiling and the prevailing heat transfer is nucleate boiling, and the surface temperature is a little above the boiling temperature. Through solving inverse problems, heat flux densities and heat transfer coefficients are calculated for a self-regulated thermal process in two different ways: with regard to the difference between the surface temperature and boiling temperature and with regard to the difference between the surface temperature and fluid temperature. At the first approach we get real values of heat transfer coefficients, at the second, effective ones. The real heat transfer coefficients can differ from effective ones by ten times. The real heat transfer coefficients give the real view of cooling. Effective heat transfer coefficients can be used for the calculation of core's cooling time for parts to be quenched. For this purpose, a known generalized dependence is used, which includes average value of Kondratjev number Kn. Kn, together with critical heat flux densities, characterizes the cooling capacity of the quenchant.

Key-words: - self-regulated thermal process, heat transfer coefficient, inverse problem

1 Introduction

There is a number of publications in which the calculation of the quenching process time includes the generalized numbers Kn and Bi_V. It has been shown that the specified numbers for nucleate boiling do not depend on the size of a part to be quenched. It has been stated that Kn can characterize the cooling capacity of the quenchant. To clarify the nature of these concepts, we made special studies on the determination of effective and real heat transfer coefficients for different sizes of cylindrical samples during non-stationary nucleate boiling. The data are obtained through solving inverse problems with the use of modern achievements in this field. As a result of such studies it has been established that there exists average values of Kn, which can be successfully used in calculation of the cooling time for parts to be quenched.

2 Method of solving inverse problems

By the present time the regularization algorithms have been developed, which have allowed to solve inverse problems that earlier posed a lot of complications. For many problems, solution existence and uniqueness have been proved and algorithms for the search of regularization parameter α have been provided. The convergence of various regularization algorithms has been proved [1,2,3]. For such inverse problems the regularization method is reduced to the addition of the regularization term to the discrepancy functional to be minimized:

$$F_\alpha[u] = \|Au - f\|_m^2 + \alpha\|u\|_C^2 , \qquad (1)$$

where u is a vector of parameters to be found, F is a discrepancy functional to be minimized, f is a vector of experimental data, A is a matrix of transformation from parameters to be found to experimental data in points of data measurement, $\|\cdot\|_m$ is a norm in space R^m, $\|\cdot\|_C$ is a norm defined as follows: $\|u\| = (Cu,u)^{1/2}$, where C is a positively determined matrix, set with regard to the process. For example, it can be assumed that C=E, where E is a unit matrix.

We developed Software IQLab for solving inverse problems (IP) [4]. For solving inverse problems, IQLab implements the Newton-Gauss method of the evaluation of non-linear parameters combining with the Tikhonov's regularization method [1,2]. The program solves both direct and inverse problems and presents results in charts and tables.

For finding heat transfer coefficients the experimental and calculated data on surface temperature from Ref. [5] were used. The calculated values of temperature at the beginning and end of self-regulated thermal process and its time with regard to the sizes of cylindrical samples are presented in Table 1.

Table 1. Surface temperature range during self-regulated process for specimens of different diameters (¼" - 2 ½")

Diameter, in. (mm)	ϑ_{I}, °C	ϑ_{II}, °C	t_{nb}, s	Surface temperature range during self-regulated process
¼" (6.35)	17	3.66	1.7	117 - 104
½" (12.7)	14	3.66	6.24	114 - 104
1" (25.4)	11.4	3.66	21.5	111 - 104
2" (50.8)	9.3	3.66	72	109 - 104
2 ½" (63.1)	8.7	3.66	104	109 - 104

The effective heat transfer coefficients for the self-regulated thermal process, calculated on the basis of solving inverse problems, are presented in Tables 2- 6.

Table 2. Effective heat transfer coefficients and generalized Biot numbers for cylinder of ½ " diameter

Time (s)	Fo	Θ	Temp Center	Alpha eff	Bi_V eff
0.000	0.000	1.0	860	0	0.000
0.709	0.094	0.9	776	37133	3.706
0.938	0.125	0.8	692	29613	2.956
1.166	0.155	0.7	608	24326	2.428
1.420	0.189	0.6	524	19870	1.983
1.723	0.229	0.5	440	15775	1.575
2.110	0.281	0.4	356	11827	1.181
2.658	0.353	0.3	272	7923	0.791
3.606	0.479	0.2	188	4017	0.401

Table 3. Effective heat transfer coefficients and generalized Biot numbers for cylinder of 1" diameter

Time (s)	Fo	Θ	Temp Center	Alpha eff	Bi_V eff
0.000	0.000	1.0	860	0	0.000
2.718	0.090	0.9	776	19144	3.822
3.629	0.121	0.8	692	15272	3.049
4.539	0.151	0.7	608	12546	2.504
5.550	0.184	0.6	524	10249	2.046
6.754	0.224	0.5	440	8139	1.625
8.290	0.275	0.4	356	6106	1.219
10.455	0.347	0.3	272	4097	0.818
14.182	0.471	0.2	188	2088	0.417

Table 4. Effective heat transfer coefficients and generalized Biot numbers for cylinder of 1 ½ " diameter

Time (s)	Fo	Θ	Temp Center	Alpha eff	Bi_V eff
0.000	0.000	1.0	860	0	0.000
6.061	0.090	0.9	776	12963	3.881
8.108	0.120	0.8	692	10340	3.096
10.150	0.150	0.7	608	8494	2.543
12.420	0.183	0.6	524	6939	2.078
15.120	0.223	0.5	440	5511	1.650
18.563	0.274	0.4	356	4135	1.238
23.406	0.346	0.3	272	2777	0.831
31.719	0.468	0.2	188	1419	0.425

Table 5. Effective heat transfer coefficients and generalized Biot numbers for cylinder of 2" diameter

Time (s)	Fo	Θ	Temp Center	Alpha eff	Bi_V eff
0.000	0.000	1.0	860	0	0.000
10.748	0.089	0.9	776	9817	3.919
14.383	0.119	0.8	692	7830	3.126
18.011	0.150	0.7	608	6432	2.568
22.040	0.183	0.6	524	5254	2.098
26.831	0.223	0.5	440	4173	1.666
32.936	0.274	0.4	356	3132	1.250
41.518	0.345	0.3	272	2104	0.840
56.218	0.467	0.2	188	1077	0.430

Table 6. Effective heat transfer coefficients and generalized Biot numbers for cylinder of 2 ½ " diameter

Time (s)	Fo	Θ	Temp Center	Alpha eff	Bi_V eff
0.000	0.000	1.0	860	0	0.000
16.811	0.089	0.9	776	7912	3.949
22.487	0.120	0.8	692	6310	3.149
28.150	0.150	0.7	608	5183	2.587
34.438	0.183	0.6	524	4234	2.113
41.914	0.223	0.5	440	3363	1.678
51.435	0.273	0.4	356	2524	1.260
64.812	0.345	0.3	272	1696	0.846
87.689	0.466	0.2	188	868	0.433

The comparison of real and effective heat transfer coefficients for cylindrical samples of ½ " and 1" diameter is presented in Tables 7 and 8.

Table 7. Comparison of real and effective heat transfer coefficients during cooling a cylinder of ½ ” diameter

Time(s)	Fo	Θ	Temp Center	Alpha eff	Alpha boil	Bi_V eff	Bi_V boil
0.000	0.000	1.0	860	0	0	0.000	0.000
0.685	0.091	0.9	784	38115	272408	3.804	27.189
0.895	0.119	0.8	708	30795	225379	3.074	22.495
1.099	0.146	0.7	632	25719	192763	2.567	19.240
1.319	0.175	0.6	556	21508	165529	2.147	16.522
1.571	0.209	0.5	480	17697	140566	1.766	14.030
1.876	0.249	0.4	404	14073	116334	1.405	11.611
2.269	0.302	0.3	328	10524	91890	1.050	9.172
2.830	0.376	0.2	252	6993	66490	0.698	6.636
3.820	0.508	0.1	176	3460	39247	0.345	3.917

Table 8. Comparison of real and effective heat transfer coefficients during cooling a cylinder of 1” diameter

Time(s)	Fo	Θ	Temp Center	Alpha eff	Alpha boil	Bi_V eff	Bi_V boil
0.000	0.000	1.0	860	0	0	0.000	0.000
2.624	0.087	0.9	784	19649	169538	3.922	33.843
3.460	0.115	0.8	708	15881	140624	3.170	28.071
4.272	0.142	0.7	632	13264	120550	2.648	24.064
5.148	0.171	0.6	556	11093	103784	2.214	20.717
6.150	0.204	0.5	480	9129	88410	1.822	17.649
7.360	0.245	0.4	404	7262	73478	1.450	14.668
8.918	0.296	0.3	328	5436	58397	1.085	11.657
11.133	0.370	0.2	252	3619	42694	0.722	8.523
15.016	0.499	0.1	176	1802	25801	0.360	5.150

3 Calculation of Cooling Time for Parts to Be Quenched

The calculation of cooling time for parts to be quenched can be done by the known Equation (2). As is known, the theory of the regular heat conditions describes the process of cooling for bodies of different shapes. The time of cooling of such bodies can be evaluated on the basis of the dimensionless dependence proposed by the author of Ref. [5]:

$$Fo_v\ Kn = \left[\frac{k\ Bi_v}{2.095 + 3.867\ Bi_v} + \ln\theta\right]$$

or (2)

$$t = \left[\frac{k\,Bi_v}{2.095 + 3.867\ Bi_v} + \ln\frac{T_0 - T_C}{T - T_C}\right]\frac{K}{a\,Kn}\ .$$

Where t - cooling time;

Fo_v - generalized Fourier number;

Bi_v - generalized Biot number;

k= 1, 2, 3 - correspondingly to bodies of plate, cylindrical and spherical shape;

K - Kondratjev form coefficient (Table 9);

Kn - Kondratjev number;

a - thermal diffusivity;

T_0 - initial temperature of heated part;

T_C - temperature of the medium;

T - current temperature.

Table 9. Functions for the analytical calculation of Kondratjev form coefficient (K)

Body shape	K
Infinite plate, thickness of L = $2R$	$\frac{4R^2}{\pi^2}$
Infinite cylinder	$\frac{R^2}{5.783}$
Ball	$\frac{R^2}{\pi^2}$

The degree of intensive cooling can be characterized by Bi_V number or by Kondratjev number Kn. There is a universal interrelation between these numbers

$$Kn = \Psi \cdot Bi_V = \frac{Bi_V}{\sqrt{Bi_V^2 + 1.437 Bi_V + 1}}$$

Finite plate, dimensions of sizes: L_1, L_2, L_3	$\frac{1}{\pi^2\left(\frac{1}{L_1^2}+\frac{1}{L_2^2}+\frac{1}{L_3^2}\right)}$
Cube	$\frac{L^2}{3\pi^2}$
Finite cylinder, height: Z	$\frac{1}{\frac{5.783}{R^2}+\frac{\pi^2}{Z^2}}$

The cooling time for cylindrical samples calculated by Eq. (2) is presented in Table 10. The error of calculation is within 1%, providing that the average Kn =0.9.

Here the relative temperature of the cylinder center changed by two times.

Table 10. Time of cooling cylindrical samples from 860°C to 440°C (Kn=0.9)

Diameter, in. (mm)	Numerical calculation (s)	Analytical calculation (s)	Error, %
½” (12.7)	1.723	1.696	-1.59
1” (25.4)	6.754	6.782	0.4
1 ½” (38.1)	15.12	15.25	0.91
2” (50.8)	26.83	27.13	1.1
2 ½” (63.5)	41.91	42.3	0.93

4 Discussion

As one can see from calculations presented, the surface temperature during boiling changes insignificantly and it is very difficult to record such changes in practice. Therefore, one can use boundary conditions of the first kind, assuming that the surface temperature of the part to be quenched is equal to the quenchant boiling temperature. One can also use effective values of heat transfer, if for practical use the generalized dependencies have been found. One of such generalized dependences can be Kn. This number can characterize the cooling capacity of the quenchant.

In view of this problem, the promising way is solving conjugate problems.

5 Conclusion

1. The cooling capacity of quenchants is characterized by a number of values: q_{cr1}, q_{cr2}, heat transfer coefficients for film and nucleate boiling, and convection. To organize the self-regulated thermal process, it is necessary for the heat flux density at the time of immersing the heated body into the quenchant to be less than the first critical heat flux density. The self-regulated thermal process is to be understood as the non-stationary nucleate boiling at which the part's surface temperature reduces rapidly to almost the fluid's boiling temperature and remains at this level for a long time.
2. Effective and real heat transfer coefficients have been determined for the self-regulated thermal process. Effective heat transfer coefficients can be less than real ones by ten times.
3. Effective values of numbers Bi_V and Kn do not depend on sizes of cylindrical samples.
4. Using the average value of effective Kn, one can make calculations of the cooling time for parts to be quenched.
5. The heat transfer coefficients can be found through solving conjugate heat transfer problems. This approach is especially efficient in case of intensive quenching, when the convection prevails.

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