Надані результати чисельного інтегрування процесу охолодження газу під час утилізації відходів. Фізична модель охолодження базується на уприскуванні рідини відцентровими форсунками. Досліджена розрахункова область, яка обмежена стінками теплообмінника. У контрольних перетинах одержано розрахункові значення температури парогазової суміші і масової частки водяної пари, які вказують на ефективність охолодження газу пропонованим способом

Ключові слова: утилізація відходів, екологічна безпека, зниження рівня діоксинів, математичне моделювання газодинамічних процесів

Представлены результаты численного интегрирования процесса охлаждения газа при утилизации отходов. Физическая модель охлаждения базируется на впрыскивании жидкости центробежными форсунками. Исследована расчетная область, которая ограничена стенками теплообменника. В контрольных сечениях получены расчетные значения температуры парогазовой смеси и массовой доли водяного пара, которые показывают эффективность охлаждения газа предлагаемым способом

Ключевые слова: утилизация отходов, экологическая безопасность, снижение уровня диоксинов, математическое моделирование газодинамических процессов

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NUMERICAL INTEGRATION OF THE PROCESS OF COOLING GAS FORMED BY THERMAL RECYCLING OF WASTE

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1. Introduction

The problem of recycling persistently increasing waste obviously requires relevant solutions. The situation is worsened by the significantly growing number of unsanctioned landfills with dangerous wastes. The rates with which various substances decompose in the general waste mass are not same, so the effects of individual fractions on generating the filtrate are different. It is unknown how fast since the dumping site formation the filtrate will start penetrating into groundwater; thus, by the time when the landfill is found, the harmful effects of the filtrate on environmental components can be significant. Therefore, such sites substantially decrease the ecological safety level [1] and require their recycling as quickly as possible.

A serious concern must be raised about wastes from medical institutions, which are quite epidemiologically dangerous because they contain helminth eggs and pathogenic microorganisms as well as some possibly radioactive or toxic substances [2]. No less dangerous for the environment are polymer wastes [3]. They contain carbon and its compounds; moreover, they are secondary material and energy resources, as is shown in studies [4, 5]. Wide application of plastics and polymeric materials in various industries, including consumer goods manufacturing, increases the carbon content and carbon containing compounds in wastes, so their thermal treatment enlarges the amount of various pollutants, including super toxic ones such as dioxins.

2. Literature review and problem statement

The modern industry of waste recycling uses thermal methods that are based on plasma generators [6], whereby high temperature conditions (over 1,200 °C) ensure decomposition of dioxin, which is a cumulative poison belonging to the dangerous xenobiotic group, into simple fragments [7]. However, there exists a mechanism of recrudescent, or de novo, dioxin formation, which is observed in flue gases in a temperature range from 300 °C to 450 °C. The factors of forming them include the speed of cooling such gases in the specified temperature range and the presence of chlorine and oxygen [8]. Therefore, it is possible to assume that the maximum ecological efficiency of the waste recycling process can be achieved by preventing the formation of dioxins not only at the stage of wastes' processing in the plasma reactor but at its outlet at the stage of cooling the generated gas. Thus, the most important and scientifically relevant approach is to determine those technological solutions that would ensure ecological safety of the thermal utilizing of solid waste.

There are various methods of cleaning hot flue gases. The authors of [9] disclose the process of dioxins' formation during the thermal treatment of wastes, whereas in [10, 11] there are scientifically grounded proofs of the effectiveness of dealing with them in conditions of using relevant cleaning systems. However, the latter case raises the question of the subsequent handling of the used filters. Thus, the best option is to prevent the formation of highly toxic substances as such. In [12], the authors describe a significantly wide range of modern methods of dealing with dioxins on the basis of catalytic reactions. On the other hand, the comparative analysis of those methods has revealed certain limitations – the main ones are as follows:

– the urgency of controlling the chemical composition of wastes to reduce the amount of chlorine [13], which is quite a difficult task because the composition of utility wastes does not remain the same throughout time;

– the urgency of controlling the catalyst condition for ensuring high efficiency of the catalytic process;

– the high costs of investing and recycling, which limit the scope of applying these methods.

One of the rational ways of solving these problems is to cool flue gases so fast that the thermal conditions do not become favorable for dioxin formation. However, it is rather difficult to implement such cooling in the broad temperature range. Therefore, the present study suggests exploring the possibilities of applying an evaporative heat exchanger with centrifugal nozzles that help provide dispersed liquid injection into the hot gas flow from the plasma reactor.

3. The purpose and tasks of the study

The purpose of the study is to improve the ecological safety of thermal utilizing of wastes by preventing the formation of highly toxic substances in the generated gas.

The defined purpose can be achieved by solving the following tasks:

– to analyze the reactions during the gas and dispersed phases when there happens the irrigation cooling of the generated gas to decrease the probability of dioxin formation in the process of waste recycling;

– to investigate the influence of interphase interactions on the efficiency of the suggested system of cooling the generated gas with liquid that is dispersed through centrifugal nozzles;

– to use numerical simulations in determining the efficiency of estimating the various operational modes of the proposed technological device for the irrigation cooling of the generated gas, depending on the speed of the temperature decline until its safety value.

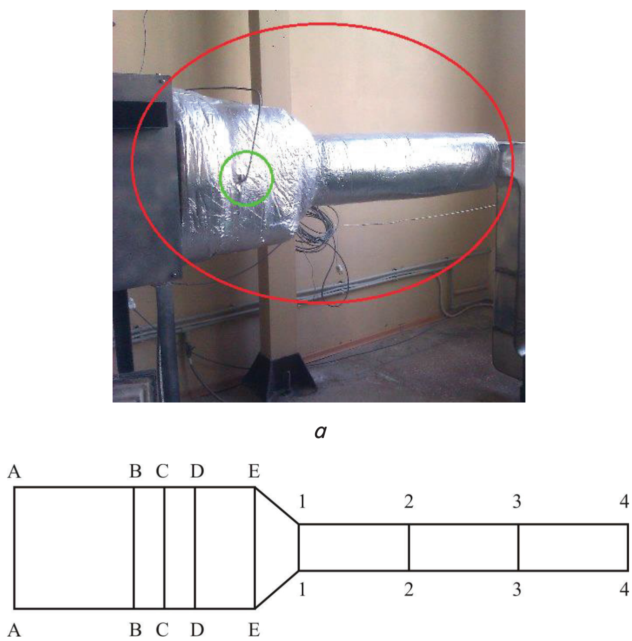
4. The materials and methods of studying the efficiency of various operation modes of the proposed technological device for the irrigation cooling of the generated gas

4. 1. Analysis of the reactions during the gas and dispersed phases and the influence of interphase interactions on the efficiency of the proposed cooling system

Issues of ecological safety that is achievable with using multiphase dispersed structures for various tasks are described in [14, 15]. Similar irrigating systems are used to ensure ecological safety during fire fighting and dust control at loading and unloading granular materials [16]. In [17, 18], the authors consider mathematical models and perform calculations of the processes. However, it is necessary to note that the tasks have been accomplished while considering some specific technical conditions and requirements. At present, there exists a general approach to the physical and mathematical formulation of this type of tasks, which is based on classical equations for calculating gas dynamics.

For the conditions of reducing the costs of the research and development of promising technologies, a numerical experiment is becoming one of the most economical and convenient methods for detailed analysis of the complex processes in gas dispersion environments. It can be implemented and the results of the generated gas cooling processes can be visualized with the help of using a mathematical apparatus that is able to reproduce adequately the complex gas dynamic processes. Since water drops in the gas flow at high temperatures will evaporate, it entails studying a two-phase multicomponent environment having phase transformations. The behavior of a single drop in a gas dynamic field is described through a system of ordinary differential equations (ODEs) [19] in which part of the parameters is functionally associated with independent variables. The system of ODEs can be completed and solved while taking into account bilateral interactions by alternating the solution of equations for the dispersed and continuous phases until the solution for both phases becomes steady in time.

The effectiveness of the water curtain for cooling the generated gas in the evaporative heat exchanger depends on the structure and parameters of the gas-drop flow. One of the operational effectiveness indicators is the value of water supply parameters for the nozzles that ensure certain water spray dispersion and the speed of the water outflow from each nozzle. Thus, it is necessary to supply water through the centrifugal nozzles into the high temperature gas flow in such a way that can be recognized as satisfactory, which means that it should provide fast gas cooling down to a safe gas temperature close to about 300 °C. The physical and mathematical description of the process can be provided, based on the classical approach to a two-phase flow movement [19–21]. The modeling of the generated gas cooling process by injecting water through the centrifugal nozzles in a hot gas flow is used in the present study to investigate the computational domain, which includes a space segment bounded by the heat exchanger walls as well as its input and output sections (Fig. 1).



a

b

Fig. 1. The evaporative heat exchanger: *a* displays the irrigating system for gas cooling (the evaporative heat exchanger); *b* shows the control sections

The mathematical model of the gaseous phase of the generated gas cooling process is presented in [19, 20]. It allows describing the features of a three-dimensional flow in the heat exchanger and shows the impact on the dispersed phase. The reactions and interrelations in the dispersed phase are analyzed on the basis of some assumptions described in [21], which allows examining the process behavior in the Lagrangian description.

The interaction between the phases is taken into account while using the discrete model "a particle vs. a cell source," according to which the presence of a drop in the gas flow manifests itself through additional sources in equations on maintaining the continuous phase [22]. The drops' trajectories are calculated while determining the values of the impetus, weight and heat that are gained or lost by "a package" of drops that move along this trajectory. Then these values are included in calculating the gas phase in the form of the source components S_m, S_q, and S_{fi} in the equations on the gas dynamics. Thus, as the gas phase influences the dispersed phase, it is essential to take into account the opposite effect of the dispersed phase on the continuous phase [21].

The obtained mathematical models of the gas and dispersed phases are the basis for numerical experiments to investigate the effectiveness of the suggested generated gas cooling system in order to improve the ecological safety of the process of recycling waste. Using the method of the numerical integration of the obtained equations of the gas phase [19, 20], it is possible to determine the gas parameters at any point of the computational domain. This allows controlling the temperature of the gas flow in specific sections of the heat exchanger and the speed of its change. Moreover, it becomes possible to determine the most rational parameters of water supply through nozzles, which facilitates a sharp decrease in the temperature of the gas flow and, consequently, increases the ecological safety of the process of recycling waste.

4. 2. Numerical integration of the gaseous phase equations

A numerical integration of differential equations in partial derivatives under given boundary conditions entails their discretization. The discretization of the equations in space was performed by the method of control volumes [23] on the basis of an unstructured (disordered) calculating net that is composed of polyhedral elementary volumes – cells.

The allocation of the drops' volumes in the spray jet is based on data from [18], and it is well-described by the Rosin-Rammler distribution. The numerical values of the nozzle water supply parameters, determined by the above-described method, for three water supply variants, which differ by the water spray dispersion and the speed of its discharge from the nozzle, are provided in Table 1. The irregular calculation net includes 77,087 polyhedral cells. We argue that the elementary volume of gas at the initial moment of time is located in the center of the cross-sectional flow part of the heat exchanger, which precedes the area of water injection (the cross-sections "C–C" in variants No. 1 and No. 2 and the cross-section "A–A" in variant No. 3).

In the process of gas cooling, the dispersed liquid drop temperature changes until it reaches the boiling point under the heat balance, which is determined by the equation:

$$m_p c_p \frac{dT_p}{dt} = \alpha A_v \left(T_\infty - T_p\right) + L\frac{dm_v}{dt}, \qquad (1)$$

where c_p is the drop heat capacity; α is the heat transfer coefficient between the drop and gas, which is defined experimentally; A_v is the drop surface area; L is the latent heat of vaporization; T_p is the drop temperature; T_∞ is the local gas temperature.

The results of experimental studies are usually used as factor dependences of Nu (Re, and Pr), where Nu is the Nusselt number. In view of equations (14) and (20) [21], equation (1) can be written as follows:

$$\frac{dT_p}{dt} = \frac{\left(T_\infty - T_p\right)}{\Theta} + \frac{Q_L}{\Theta}, \qquad (2)$$

$$Q = \frac{LSh\rho D\left(c_s - c_\infty\right)}{Nu\lambda}, \qquad (3)$$

$$\Theta = \frac{\rho_p d_p^2 c_p}{6Nu\lambda}. \qquad (4)$$

Table 1

Numerical values of the nozzle water supply parameters

Parameter name	Variant number		
	1	2	3
d_0, m	0.0006	0.0009	0.0011
$A_f/(D_s d_0)$	0.75	1.3	1
C_D	0.43	0.56	0.50
v, m/s	10	3	3
Δp, Pa	48.228	5.650	3.189
Re_e	3.858	2.257	1.957
N	3.77	3.99	3.6

When the drop temperature reaches the boiling point, it is possible to apply the boiling speed equation:

$$\frac{d\left(d_p\right)}{dt} = -\frac{4\lambda}{\rho_p c_{p\infty} d_p}\left(1 + 0.23 Re_p^{0.5} \ln\left[1 + \frac{c_{p\infty}\left(T_\infty - T_p\right)}{L}\right]\right), \qquad (5)$$

where $c_{p\infty}$ is the gas heat capacity.

In considering the elementary volume of the gas movement in the flowing part of the heat exchanger, we have generated a control spurt of the gas flow for the three variants of the dispersed liquid supply (Fig. 2) and a graph of dependence of the Z coordinate of the elementary gas volume on the time τ (Fig. 3).

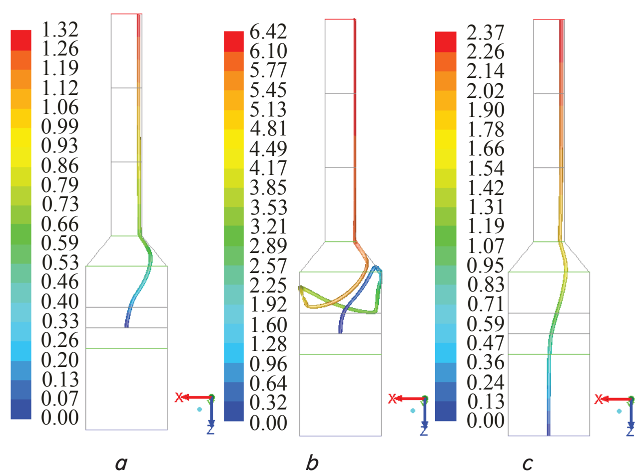


Fig. 2. The movement trajectory of the elementary gas volume (a control spurt of the gas flow): *a*–*c* are variants of dispersed liquid supply

The graph Z(τ) is used to determine the time points τ_i in which the elementary volume of gas crosses the control sections i. It has also helped determine the average gas temperature t_{av}, the coefficient of the uniform temperature distribution in gas γ_T in the control cross sections i, the stay time Δτ, and the average cooling rate Δt/Δτ of the elementary gas volume between the adjacent cross sections i and (i–1) (Table 2, 3).

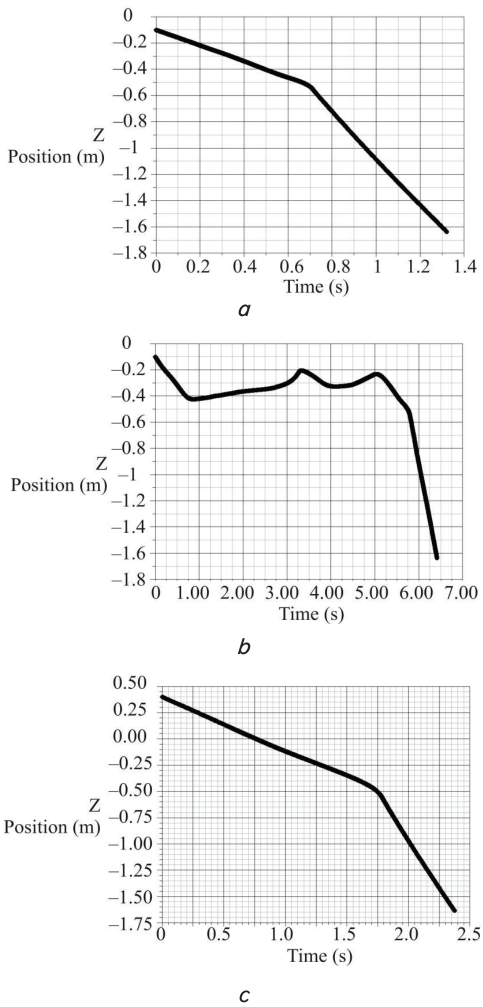


Fig. 3. Dependence of the Z coordinate of the elementary gas volume on time: *a* is variant No. 1; b is variant No. 2; c is variant No. 3

Table 2 shows that the total stay time of the elementary volume of gas in the flow section of the heat exchanger for the investigated variants is, respectively, 1.32 s, 6.42 s, and 2.37 s. The coefficient of uniformity γ_T specifies how the temperature of the gas-vapor mixture changes in the control section. If there are no changes (i. e., the maximum uniformity of distribution has been reached), γ_T=1.

Table 3

Parameters of the elementary gas volume, which are controlled between the cross sections

Parameter	Control cross section							
	A–B	B–C	C–D	D–E	E–1	1–2	2–3	3–4
Variant No. 1 of the dispersed liquid supply								
$\Delta\tau$, s	–	–	0.17	0.31	0.24	0.18	0.2	0.22
$\Delta t_{cp}/\Delta\tau$, °C/s	–	–	1,918.8	795.8	265	243.9	35.5	8.2
Variant No. 2 of the dispersed liquid supply								
$\Delta\tau$, s	–	–	0.25	0.75	4.8	0.2	0.2	0.2
$\Delta t_{cp}/\Delta\tau$, °C/s	–	–	1,268.8	596	16.5	12.5	0	0
Variant No. 3 of the dispersed liquid supply								
$\Delta\tau$, s	–0.75	0.2	0.2	0.45	0.15	0.2	0.2	0.2
$\Delta t_{cp}/\Delta\tau$, °C/s	195.1	809.5	975.0	539.6	238.7	124.5	56.5	35

The stay time $\Delta\tau$ and the average cooling rate $\Delta t/\Delta\tau$ for the elementary gas volume in the areas between the control cross sections are the necessary parameters on the basis of which it is possible to decide what flow rate of the coolant is needed.

Table 2

Parameters of the elementary gas volume, which are controlled in the cross sections i

Parameter	Control cross section								
	A	B	C	D	E	1	2	3	4
Variant No. 1 of the dispersed liquid supply									
τ, s	–	–	0	0.17	0.48	0.72	0.9	1.1	1.32
t_{av}, °C	1,200	1,199.8	1,180.4	854.2	472.2	408.6	364.7	357.6	305.8
γ_T	1	0.999	0.985	0.792	0.728	0.815	0.899	0.938	0.961
Variant No. 2 of the dispersed liquid supply									
τ, s	–	–	0	0.25	1	5.8	6.0	6.2	6.42
t_{av}, °C	1,200	1,200	1,200	882.8	436.0	356.9	354.4	354.4	354.4
γ_T	1	1	1	0.813	0.839	0.964	0.992	0.995	0.997
Variant No. 3 of the dispersed liquid supply									
τ, s	0	0.75	0.95	1.15	1.6	1.76	1.96	2.16	2.37
t_{av}, °C	1,200	1,053.7	891.8	696.8	454.0	418.2	393.3	382.0	375.0
γ_T	1	0.985	0.970	0.947	0.885	0.917	0.951	0.972	0.984

5. The results of studying gas dynamic processes in the evaporative heat exchanger during the irrigation cooling of the generated gas

The maximum cooling of gas occurs during its contact with droplets of the dispersed and evaporating liquid under the following conditions:

– for variant No. 1, the gas temperature decreases to 472 °C at 0.47 s of its presence between the cross sections C and E;

– for variant No. 2, the gas temperature decreases to 436 °C at 1.0 s of its presence between the cross sections C and E;

– for variant No. 3, the gas temperature decreases to 454 °C at 1.6 s of its presence between the cross sections A and E.

The maximum speed of cooling in all variants is observed between the crossings C and D (Fig. 4) at the top values of 1,919 °C/s, 1,269°C/s, and 975 °C/s for variants No. 1, 2, and 3, respectively (Fig. 5). The rest of the time is taken for mixing the gas with the water vapor.

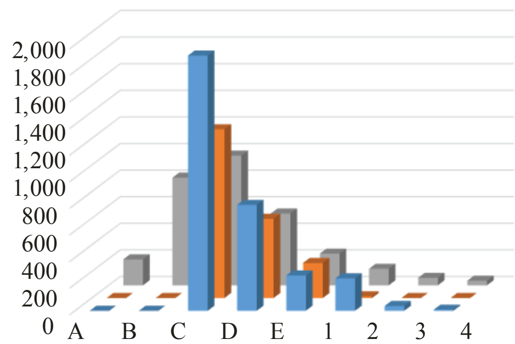


Fig. 4. The average cooling rate of gas (°C/s) between the control cross sections: ● for variant No. 1 of supplying dispersed water; ● for variant No. 2; ● for variant No. 3

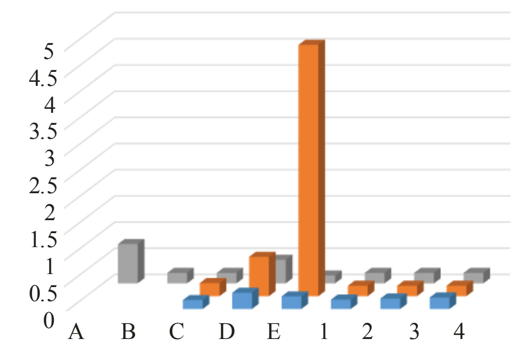


Fig. 5. The gas stay time (s) between the control cross sections: ● for variant No. 1 of the dispersed water supply; ● for variant No. 2; ● for variant No. 3; A, B, C, D, E, 1, 2, 3, and 4 are the control cross sections

The best quality of mixing is achieved in variant No. 2 (the uniformity coefficient is equal to 0.997) due to the extended stay of the gas between the sections D and E because of the presence of circulating currents there.

6. Discussion of the results of the numerical integration of equations describing gas-dynamic processes in the tested heat exchanger

This study is part of scientific research for creating an ecologically safe technology of recycling waste. It is initially based on [15, 19–21], which suggest a mathematical model of a three-dimensional flow of a gas-dispersion fluid with a phase transformation (evaporation) and an interphase interaction. The model determines, qualitatively and clearly, the main features of cooling generated gas by injecting some dispersed liquid into its environment. This mathematical model of studying the trajectory of the coolant drops allows monitoring the changing impulse, the weight, and the heat of a set of drops as well as the temperature of the gas-vapor mixture at various time points of the gas stay in the heat exchanger. The main advantage of this method of ensuring ecological safety during thermal waste utilization is prevention of those temperature modes that would facilitate dioxins formation, which makes it distinct among other methods – those that use complex filters or catalytic reactions.

The results of the numerical tests show that the second variant of supplying dispersed coolant is characterized by the shortest time of establishing equilibrium in the vapor mixture, which reduces the coolant expenditure and prevents its accumulation in the heat exchanger. However, in terms of ecological safety, the most satisfactory variant is No. 1 because the time of cooling the gas flow from a temperature of 1,200 °C down to a temperature that is close to being safe, i. e. 305.8 °C, is 1.32 s. It is clear that the suggested mathematical models of the processes that occur in the heat exchanger produce quite satisfactory results within the research task and show the possibility of its solving.

The completed tests do not exclude the possibility of determining the most efficient variant, which can be subsequently found after formulating and solving a relevant optimization problem.

7. Conclusions

1. The study has scientifically justified a reasonable possibility of using technological devices that can ensure a fast cooling of flue gases by preventing temperature conditions for dioxins formation and thereby increasing the ecological safety level. Therewith, the physical model of such cooling is based on injecting cooling liquid from centrifugal nozzles into the gas flow.

2. In order to optimize the parameters of the suggested technological device for the irrigation cooling of the generated gas, the present study involves numerical simulations that help evaluate the device effectiveness by determining the factor of the temperature decrease rate down to a safe value in various modes in a given segment of space that is limited by the heat exchanger walls. The numerical simulations are made on the basis of [19–21], which provide mathematical models of interphase interactions of gas-dynamic processes in an evaporative heat exchanger; such models describe the changing impulses, the weight, and the heat of drop sets and also the temperature of the gas-vapor mixture at various time points of gas staying in the heat exchanger.

3. The undertaken numerical experiment shows that the use of the device can reduce the gas temperature by 895 °C in 1.32 s if the spray diameter of a nozzle is 0.6 mm and the coolant injection rate is 10 m/s. The maximum gas cooling occurs during the gas contact with evaporating dispersed fluid droplets. However, a higher coefficient of gas temperature uniformity γ_T=0.997 (compared to

γ_T=0.961) at the outlet of the heat exchanger is observed in the variant in which the spray diameter of a nozzle is 0.9 mm and the coolant injection rate is 3 m/s. This means less time for establishing the equilibrium in the vapor-gas mixture, less consumption of the coolant, and non-accumulation of the vapor-gas mixture in the heat exchanger.

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