Development of the highly boosted capillary porous foam generator for gas (steam) mechanical foam

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Abstract. A highly boosted capillary porous foam generator for gas (steam) mechanical foam is developed. It contains the inlet and outlet nozzles, nozzles for supply of the foam generating solution and foam discharge, package of the foam generating meshes with increased sizes and sprayer. In order to increase capacity and improve the foam characteristics, the generator is equipped with a capillary patch and forming channel. The capillary patch is located at the external surface of perforated pipe that supplies the foam generating solution, and the forming channel is installed outside of the capillary patch with feeder. Additionally, the foam generator has control plates located at both sides of the feeding device, where the plates at both sides pass into a spring guiding viewfinder, also the packet of foamed grids with increasing size in the direction of gas flow is made with dimensions 0.4x0.55.

1. Introduction

A foam generator of a new class is proposed - a nozzle-shaped one, having a capillary-porous structure specially optimized for foam generation instead of the usual mesh package. To do this, it was necessary to study the internal characteristics of the process of boiling liquid in capillary-porous structures: firstly clean [3-6], then with the addition of a additives [4, 7-13]. Experimental data were summarized using dimensional analysis with obtaining a criterial equation [7]. Nozzle-free foam generators have some peculiarities as follows: they are able to manage power processes [1, 4, 13], have defoaming structures [8], able to generate foam with the help of bubbling processes [9] and supply of power instead of gas [11], as well as have special materials with controlled geometry of micro channels [12].

The invention refers to the industrial and station heat and power, and designed for generation of two flows at the heat and power units, that could be used in fire engines for firefighting inside buildings and facilities, as well as be useful in the different fields of national economy for dust suppression [6, 10].

It is known that the similar invention was introduced in USSR 1202598 A62C 5/04, 1985, which contains inlet and outlet nozzles, package of meshes, sprayer in the form of tubular ring.

One disadvantage of the device is its low foam efficiency characterized by the limited penetration of the foam generating solution through the transverse section of meshes located in the tubular ring. In addition, the characteristics of the foam turned out to be low, since the package of standard metal grids does not allow turbulization and intensify the processes of foam generation. Besides, the boosting
action of turbulator looks insignificant because the fluid flow in the meshes section is uneven and unstable. It is also impossible to control a fluid rate. Thus, the foam features come short of the expected ones. However, it is possible to increase efficiency of the foam generator and enhance its operational characteristics.

The similar invention USSR 1498511 A 62 C 5/04, 1989, which contains inlet and outlet nozzles, nozzles for supply of the foam generating solution and foam extraction, sprayer, package of the foam generating meshes in the form of turbulator with the expanded mesh cells along the foam flow.

2. Installation description and specifics
Foam generator is equipped with the capillary patch and forming channel in order to increase efficiency of the foam generator and improve the foam features. The capillary patch is located at the external surface of perforated pipe of foam generating solution, and the forming channel is located outside of capillary patch forming a feeder. In addition, foam generator contains the adjusting plates located at both sides of the feeding device whereas the plates at both sides transfer to the spring deflector, and package of foam generating meshes with extended sizing along the gas flows of 0.4x0.55.

Compared with the known technical solution in the proposed device due to the use of a perforated pipe for supplying a foam solution, the flow of fluid is significantly increased, rather than through the end of a packet of grids located in a tubular ring. Since there is a capillary patch at the external surface of the pipe that has capillary size dozens of times less than the size of metal cells, then a quite balanced transpiration of the increased fluid consumption is ensured into the forming channel, which serves as a feeder for the foam generating mesh package [7, 11]. That helps significantly increase efficiency and stability of film of the foam generating solution, in the mesh package 0.4x0.55, and therefore increases such features as frequency and dispersion.

Additionally, installed adjusting plates help control a fluid consumption rate and therefore the important internal foam characteristics (critical and detachable size of bubbles, their lifetime and silence, frequency of generation, density of the forming centers) [2, 3, 5]. The above values determine the device characteristics: specific foam efficiency, stability and steadiness of foam, frequency and dispersion. Upgrade of the mesh package 0.4x0.55 help reduce a gas dynamic resistance in comparison with prototype and retain a hydraulic resistance.

This is to emphasize that the significant enhancement and boosting of the foam generating process is ensured by the available spring deflector that creates spontaneous vibrational forces because of the gas flow. The last ones jointly with the capillary, gravity and inertial forces of pressure create a quite stable two-phase multicomponent pulse heat-and-hydrodynamic boundary layer that generates foam with high efficiency and enhanced characteristics.

Consequently, by increasing the specific performance and improving the foam performance, the material consumption and dimensions of the device are reduced, energy is saved by pumping the solution and gas due to the possibility of controlling the process of foam generation, especially with forced and variable modes of operation of the foam generator, the reliability and service life of the device increases.

Figure 1 describes a foam generator in plain view. Foam generator consists of inlet 1 and outlet 2 nozzles, package of the foam generating meshes 3, made of two metal standard meshes of capillary porous structure, each consequent mesh has an increased size of cells along the gas flow direction 0.4x10^{-3}m; 0.55x10^{-3} m accordingly. The sprayer body 4 includes capillary patch 5, located at the external surface of perforated pipe 6 and forming channel 7, located outside of capillary patch 5 forming a feeder 8 with plates 9 at both sides, transferring to the spring deflector 10.
Figure 1. Highly-boosted nozzle-free capillary porous foam generator of gas (steam) mechanical foam.

Foam generator runs in the following sequence as follow: The foam generating solution 13 is injected by sprayer 4 to the package of foam generating meshes with increased sizes along the gas flow 0.4 х 10^{-3} m и 0.55 х 10^{-3} m accordingly.

Solution is transported through the holes of perforated pipe 6 via capillary patch 5 and approaches feeder 8, formed by patch 5 and forming channel 7. It helps pump large volume of the foam generating solution 13 and quite evenly re-distributes it, feeding the mesh package 3. Fluid 13 in the mesh package begins distribution in a form of stable and steady films because of the joint action of the gravity and capillary forces.

The vibrational potential occurs as a result of spontaneous vibrational (wave) action of the spring deflector 10, streamlined by the gas flow 11 in nozzle 1 and foam flow 12 in nozzle 2. Sound waves 14 actively promote an even re-distribution of fluid 13 when it is transferred from capillary patch 5 in the mesh package 3, whereas the adjusting plates 9 help actively manage the process. Under oncoming gas flow 11 in volume and at the mesh surface 3 the gas bubbles arise and that leads to generation of two-phase flow in the form of gas mechanical foam 12, which is formed in spray with the help of attachment (not shown) and moves forward as per the process either in the heat and power unit or to the fire and dust source.

Availability of the capillary patch 5 ensures an even distribution of the foam generating solution 13 inside feeder 8, whereas an increased consumption of solution 13, pumped through pipe 6 forms a large specific capacity of foam generator. Evenly distributed thin liquid films in mesh package 3 have stable and steady features, which allows to obtain a foam of high technical characteristics such as frequency, dispersion and stability.

In comparison with prototype due to the joint action of capillary, gravity, inertial and vibrational potentials, the heat exchange factors are boosted by 1.5 times and specific capacity is increased. This helps accordingly reduce material consumption rate 1.5 times and the device dimensions, weight of device 2.5 times by saving capital expenses. Although, it leads to saving power and solution under various conditions (due to the capillary patch 5) and improved conditions due to the controlled process with the help of adjusting plates 9 and upgraded meshes 0.4 х 0.55. Therein, the operational conditions are getting simplified and the operational costs are reduced.
3. Comparative analysis of different dust collectors. Hydraulic losses specifics

In Table 1 a and b package of meshes 0.4x0.55 in size means that it is combined from two layers of wire meshes installed consequently along the incoming gas flow with cell sizes 0.4x10^{-3} m; 0.55x10^{-3} m accordingly.

The advantage of meshes with larger cells is that in smaller cells like in prototype (0.08x10^{-3} m) a.e. USSR 1498511, 1989, the foam generation process gets worse as bubbles block their cells, which leads to hydrodynamic crisis. Hence the production of fresh foam at the inlet is blocked. This picture was observed by the authors using optic research methods [1, 2, 4] (holographic interferometry and high-speed movie capturing). Package of meshes 0.4x0.55 forms quite stable two-phase multi-component hydrodynamic shear layer pulsed by heat, which is a prerequisite for high quality foam production.

Large cells like in prototype (1x10^{-3} m), lead to the abrupt reduction of value of capillary potential, liquid film becomes unstable and crisis of foam generation happens much earlier than in meshes with smaller cells 0.08x10^{-3} m.

Thus, due to boosting of the foam generation process in package of meshes 0.4x0.55, 1.5 times (see table 1) the efficiency is increased, the process is enhanced, and package of meshes is a kind of turbulizer that helps approximately 1.5 times reducing materials consumption and 2.5 times weight reduction.

In fact, enhancement of the foam generation process will be significantly higher due to the spring directing shield, which influences upon the adjusting plates installed at both sides of the feeding device and lead to more active and stable supply from foam generating package of meshes via liquid solution. Mutual impact on the process of the gravity, capillary, inertial and vibration potentials is observed. In case of vibration movements of surface cause by vertical cylinders, enhancement of processes may increase two times, and in some cases up to ten times [14].

| Table 1. Comparative analysis of different dust collectors. | a) |
|---|---|---|---|---|---|
| No. | Indicator | Chamber of gravitational dust collector | Inertial (centrifugal) dust collector | Cyclone (centrifugal medium-pressure) Large diameter (1-3m) | Small diameter and battery type |
| 1 | Hydraulic resistance, Pa | 100-200 | 200-300 | 700-800 | 800-1250 |
| 2 | Minimum size of collected particles, 10^{-6}m and effectiveness (ƞ%) | 50-100 | 40-50 | 30-40 | 10-25 |
| 3 | Maximum admissible temperature, °C | 400 | 400 | 400 | 400 |
| 4 | Gas low limit temperature (as per steel grade) | Over dew point | 85 | 85 | 85 |
| 5 | Corrosion resistance | Too resistant | Any | Minor |
| 6 | Explosion and Fire Hazard | | | | |
| 7 | Relative cost of cleanup of 1000m³ gas | 1 | 1.5 | 2 | 3 |
| 8 | Main settling mechanism | G | U | U | U |
| 9 | Dependency of effectiveness from: a) particle size | | ~d², Ck ~ d², Ck | | |
| | b) temperature | | | | |
| | c) concentration (g/m³) | No impact | | As per device diameter and dust adhesion |
| | d) humidity upon condensate of water vapors | No impact | | Discharge might be complicated |
| 10 | | | | | |
| No. | Indicator                        | Hose (fiber) filter | Granular filter | Wet filter | Wet Dust Collector Low pressure | Wet Dust Collector High pressure | Electric filter | Wet filter of Author |
|-----|----------------------------------|---------------------|----------------|-----------|-------------------------------|-------------------------------|----------------|----------------------|
| 1   | Hydraulic resistance, Pa         | 750-1500            | 1200-1600      | 1000-1800 | 750-1500                      | 5000-12500                    | 100-400        | 500-1000             |
|     | Minimum size of collected        | 0.5                 | 0.1-1          | 1-2       | 2.5                           | 0.1-1                         | 0.25-1         | 0.1-0.25             |
|     | particles, 10^{-m} and           |                     |                |           |                               |                               |                |                      |
|     | effectiveness (η%)               |                     |                |           |                               |                               |                |                      |
| 2   | Maximum admissible               | 99                  | 97             | 97        | 97                            | 97                            | 99             | 99                   |
|     | temperature, °C                  |                     |                |           |                               |                               |                |                      |
|     | <80                             |                     |                |           |                               |                               |                |                      |
|     | <250 for glass fibers           |                     |                |           |                               |                               |                |                      |
| 3   | Gas low limit temperature        | Any                 |                |           |                               |                               |                |                      |
|     |                                  |                     |                |           |                               |                               |                |                      |
| 4   | Corrosion resistance             | Resistant at temperature exceeding dew point | Required corrosion protection if acids available in gases | Resistant at temperature exceeding dew point |
| 5   | Explosion and Fire Hazard        | Major (hazardous)   | Minor         | Minimum   | Major                         | Minimum                      |
| 6   | Relative cost of cleanup of      | 3-3.75              | 2.5-4          | 7-10      | 2.5-5                         | 5-15                         | 7-15           | 1-2.5                |
|     | 1000m^3 gas                      |                     |                |           |                               |                               |                |                      |
| 7   | Main settling mechanism          | at d_r ≤ 3x10^{-7}m-D | Stk            | Stk       | K_d                          | D; K; Stk                      |
|     |                                  | at d_r > 3x10^{-7}m-Stk |               |           |                               |                               |                |                      |
| 8   | Dependancy of effectiveness from |                     |                |           |                               |                               |                |                      |
|     | a) particle size                 |                     |                |           |                               |                               |                |                      |
|     |                                  |                     |                |           |                               |                               |                |                      |
|     | at d < 3x10^{-7}m-C_k/d_k        |                     |                |           |                               |                               |                |                      |
|     |                                  | ~d^2 C_k            | ~d C_k         | n, 7...9 |
|     | b) temperature                   |                     |                |           |                               |                               |                |                      |
|     |                                  |                     |                |           |                               |                               |                |                      |
|     | at d < 3x10^{-7}m-C_k T_k/μ_k    |                     |                |           |                               |                               |                |                      |
|     |                                  | ~d C_k              | ~d C_k         | n, 7...9 |
|     | c) concentration (g/m^3)         |                     |                |           |                               |                               |                |                      |
|     |                                  | Not over 2g/m^3     | As per water supply system and power consumption | Limited 50                       | n, 8...11                      |
|     | d) humidity upon condensate of   |                     |                |           |                               |                               |                |                      |
|     | water vapors                     | Fiber is clogged    | Improves settling | No impact | No impact                     | Complicated dust removal      | Improves settling |
|     |                                  |                     |                |           |                               |                               |                |                      |

In particular, enhancement of hydrodynamics processes reaches up to 10 times for vibrations with low frequency (high amplitude), and with high frequency (low amplitude) [6].

Below is presented some calculation related with hydraulic resistance of the package of meshes.

The pressure loss is presented with the following:

\[
\Delta p = \mu m \rho l^{-1} F_{\epsilon}^{-1} k_{r}^{-1}, \text{ Pa}
\]  

(1)
where: $\mu = 282.10^{-6} \text{ Pa} \cdot \text{s}$ - dynamic viscosity of the liquid; $m_l = 2.4 \times 10^{-3} \text{ kg} \cdot \text{s}^{-1}$ liquid consumption for 1 m$^2$ of package of meshes; $h$ - length of layer, m; $F_c$ - cross section area of package of meshes, m$^2$; $k_y$ - relatively permeability factor, m$^2$; $\rho_l$ - density of the liquid, kg/m$^3$.

Cross section area of the package is calculated with the following:

$$F_c = \varepsilon F_C = 0.7 \times 10^{-3}, \text{ m}^2$$

where: $\varepsilon = 0.7$ is mesh porosity, $F_C = \delta L = 1.02 \times 10^{-1}$. Here $\delta$ is thickness of the package. For stainless steel meshes 12X18H9T (4 MTC - 4-7-66) thickness of package equals to 0.4 $\times$ 0.55.

Relatively permeability factor is defined experimentally [1, 2]:

$$k_y = 5.5 \times 10^{-7} \left( \frac{b_y}{d} \right)^{-1.29} = 2.1 \times 10^{-7}, \text{ m}^2$$

where $b_y$ is hydraulic diameter; $d$ average diameter of the mesh wire.

Considering equations 1, 2 and 3 for the pressure loss is obtained:

$$\Delta p = 282 \times 10^{-6} \times 2.4 \times 10^{-3} \times 1.958 \times 0.7 \times 10^{-3} \times 2.1 \times 10^{-7} = 4.8 \text{ Pa},$$

At the maximum efficiency (boosting) (see table 1):

$$\Delta p = 4.8 \times \frac{8 \times 10^4}{0.5 \times 10^4} = 768 \text{ Pa}$$

The calculated pressure loss (Eq. 4) is significantly lower than that pressure loss of the nozzle foam generators where foam generating solution is injected directly to the nozzles under pressure $2 \div 5 \times 10^5$ Pa and nearly the same as in prototype since ratio ($h_y / d$) will be slightly changed.

The pressure loss of the package of meshes for the gas flow is as follow:

$$\Delta p = \sum K \rho_y v^2$$

where $\rho$ is density of gas, kg/m$^3$; $v$ - velocity of gas phase, m/s; $K$ - minor loss coefficient ([15, 16, 17]).

The flow behavior can be established with the Reynold number:

$$\text{Re} = \frac{v_0 d}{\nu} = 62.9$$

where: $v_0$ - velocity of gas phase in cellular meshes, m/s; $d$ - average diameter of mesh wire, m; $\nu$ kinematic viscosity, m$^2$/s.

Since the Re number is higher than 50, the total minor loss coefficient is:

$$\sum K = 2.6$$

Based on the value of the minor loss coefficient, the pressure loss is:
\[
\Delta p = 2.6 \frac{1.2 (3^2)}{2} = 14.04, \text{ Pa} \quad (9)
\]

Comparing with the prototype:

\[
\text{Re} = \frac{v_0 d}{\nu} = 62.9 \quad (10)
\]

Based on the diagram [15] minor loss coefficient is 7, and pressure loss is 37.8 Pa.

4. Conclusion

The advantage from implementation of the proposed foam generator in comparison with prototype is reduction in material consumption and dimensions by 1.5 times while the specific productivity growth achieved due to the intensification of the two-phase flow generation processes, 2.5 times the mass. At nominal mode of operation, the hydraulic resistance will be as in the prototype, but hundreds of times lower than in the injector generators, and the gas-dynamic resistance is 2.7 times less than in the prototype. Simplification of installation (no heater) leads to a reduction in operating costs, simplifies the structural design of the foam generator, increases its reliability and service life. A stable two-phase multicomponent pulse immersion enhances the internal and technical characteristics of device. Under various and emergency operational conditions a proper control of the foam generation process is ensured, and results in power saving when supplying gas and solution, and also saves the foam generator and reduces operational expenses.

Overall, the proposed foam generator reduces power and material consumption, increases the foam quality, simplifies operational conditions and ensures the process safety and protects environment (social effect).

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