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COALESCENCE OF OIL MIST DROPLETS IN NON-STATIONARY AIR FLUX

The mechanism of oil mist formation in metal mechanical working process is described and its influence on the industrial safety characterized. It has been shown that the search for new solutions allowing to increase the separation efficiency of finely dispersed particles of liquid aerosols by preliminary coalescence is necessary. Aeromechanic factors enhancing the coalescence intensification have been analysed, and a method of coalescence of oil mist droplets by putting a two-phase (air–oil drops) flux into pulsation has been presented. The methods for the verification of the concept suggested and the appropriate measuring devices have been described. The paper includes also the results of investigations on the coalescence degree of the oil mist particles carried by non-variable air flow, characterized by low frequency pulsations.

1. INTRODUCTION

Intensification of "mist removal", which consists of the separation processes of minute liquid droplets from industrial gases emitted to the atmosphere, is one of the most essential problems in the ambient air protection. Until recently this process was almost exclusively applied in purification of flue gases emitted in technological processes of chemical industry, and in production of sulphuric acid, in particular.

It may be stated in general, that the problem of mist removal was technically solved for aerosols containing large droplets (greater than 1 μm). In this case the mist removal (i. e. by filtration) can be achieved in relatively small device, at low flow resistance and gives satisfactorily high efficiencies. High efficient ($\eta = 98\text{–}99\%$) separation of finer mists ~~by~~ filtration is possible, although energy-consuming due to high flow resistance reaching 14 kPa [5]. Separation of oil mist from the air extracted from the machine tools is a case representative of the problems discussed. This mist results from the evaporation of oil coolants used in mechanical working. If the machine tools are not equipped with casings,

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the oil mist is emitted directly to the ambient air, being a serious hazard to the safety service (slippery floors and chucks and even the possibilities of fires) and health (toxic effect on human organisms) of workmen. If the machine tools have casings for extraction of the air polluted with mist which generated during mechanical working, the aerosol formed should be directed to mist separators, while the purified air may be discharged to the atmosphere or recirculated to the engine room. Because of highly different conditions of oil mist generation, e. g. due to high temperature gradients in the tool and in the detail being worked, the particle size distribution of the mist is relatively large (0.5–4.0 μm), those below 1 μ being dominant (~70%). To make easier the separation of oil mist by conventional methods (filtration or separation in scrubbers), it is advisable to conduct eventually primary correction of mist droplet size by increasing it. This may be done among others by their intense coalescence. Having this in mind, a concept of a preliminary coalescence of oil mist particles has been doveloped. In this case the coalescence is achieved by changing the steady flow of gases being purified into non-stationary one caused by low frequency pulsations.

2. ANALYSIS OF AEROMECHANICAL FACTORS RESPONSIBLE FOR COALESCENCE OF PARTICLES

The movements of particles in a dispersion system generate around them heterogeneous, aerodynamic interacting fields. Forces of the aerodynamic interaction of particles make difficult their mutual approach at low velocity (small Reynolds numbers) and facilitate it at high Reynolds numbers.

A particle entrained into the aerodynamic wake falls down much faster than the free settling one. This effect of entrainment results in a gravitational coalescence of particles having similar masses, if their centres of gravity lie on a common line of gravity field forces. Gravitational coalescence is also possible if a smaller particle gets into the wake. In this case, however, it is an orthokinetic coalescence — the collisions are one-side oriented.

In coalescence processes the role of the effect of entrainment into the wake may be multiplied by generation of forces that direct the light particles into the wake of heavy ones in the dispersed medium. Such forces may — among others — be produced by turbulence of dispersion medium (continuous phase), that may become the source of perikinetic coalescence in which collisions of particles resulting in the stable unions have not any preferential direction in the space. If the Kolmogorov's turbulence scale λ is smaller than or equal to the sizes of particles, then one deals with a turbulent fluctuation of particles (analogical to Brownian movement). This fluctuation may bring about the entrainment of particles into the wake or accelerate electrostatic coalescence by destroying the envelope of the moving particle [6].

From physical viewpoint the effect of turbulence on the intensification of coalescence process consists in the fact that the concentrations of particles in the space increase locally (due to fluctuations), leading — among others — to the change in coalescence rate, if compared to the stationary conditions. Hence, it accelerates the particle diameter growth.

3. CONCEPT OF COALESCENCE OF OIL MIST PARTICLES

The considerations presented incline us to put a hypothesis that the coalescence process may be intensified by increasing the turbulence degree of the flowing aerosol (polydispersive one, in particular). In case of gas stream it may be done, among others, by forcing the pulsation applying periodic disturbances produced by a mechanically rotating diaphragm, placed in the conduit supplying the flux of air containing oil mist. The resulting non-stationary, pulsating flux is characterized by a constant velocity direction with a periodically changing modulus (fig. 1). Thus, the velocity oscillates in time t around the mean value $\bar{u}$. According to the literature [2, 3], pulsation of flux intensifies its turbulence, in the degree being highly dependent on the pulsation frequency. The highest turbulence fluctuations may be achieved at low frequency pulsations [2], in general not exceeding 20 Hz. Within this frequency range the degree of turbulence in pulsating flux (behind the pulsator) increases even by 50%.

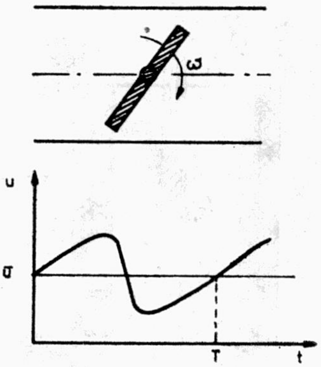


Fig. 1. Characteristics of non-stationary flux
Rys. 1. Charakterystyka strumienia niestacjonarnego

Thus, it should be assumed that the creation of a non-stationary flow of aerosol (air-oil mist) by bringing it into low frequency pulsations may intensify the oil mist coalescence.

4. METHODS OF VERIFICATION

In order to verify the hypothesis, an attempt has been made to determine qualitatively the effect of turbulent fluctuations induced by pulsation of a two-phase flux consisting of air and oil mist particles (of the following grain distribution [1]: 0.5–1.0 μm — 70%, 1.0–2.0 μm — 5–10%, 2.0–4.0 μm — 20–25%) on the relative changes in the particle sizes.

Coalescence of oil mist was examined in the system presented schematically in fig. 2. The air taken from the interior of laboratory hall was mixed with the oil mist produced in a generator, the structure of which and operation principle are presented in fig. 3.

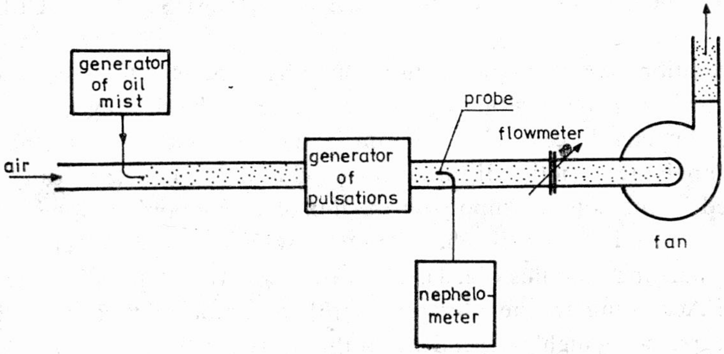


Fig. 2. Testing device for oil mist coalescence in non-stationary flux

Rys. 2. Stanowisko do badań koalescencji mgły olejowej w niestacjonarnie przepływającym strumieniu powietrza

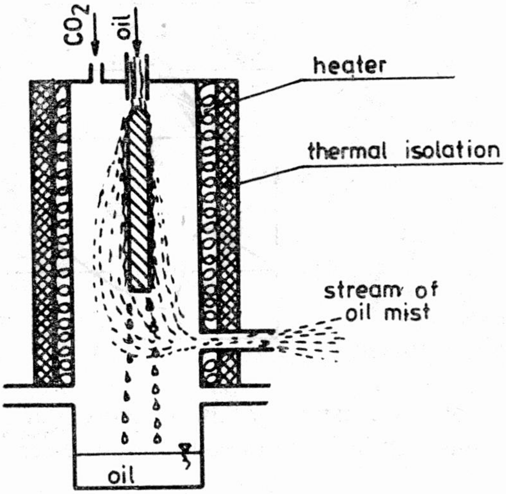


Fig. 3. Generator of oil mist

Rys. 3. Generator mgły olejowej

The aerosol produced in this way simulated the mixture of air and oil mist extracted from the casing of machine tool. The aerosol flew next in a pipeline to the system (fig. 4) in which the disturbances (pulsations) of flow were generated. Samples of gas containing oil mist were taken with a probe and directed to nephelometer to determine the coalescence degree of particles. Thereupon the aerosol flew through a constriction flowmeter and fan outside the laboratory. The flow intensity of the aerosol was constant and corresponded to the mean flow rate $\bar{u} = 14$ m/s. The investigations were carried out at different frequency of the diaphragm covering (400, 800, and 1200 min^{-1}) corresponding to the frequencies of flux pulsations ranging within 0–20 Hz. During the investigations different variants of disturbance generator structure have been applied (by changing also the area of ellyptic diaphragm, both the degree of the covering of the aerosol flow cross-section and the shape of pipeline behind the diaphragm were changed). The respective structural variants are shown in fig. 5.

Measurements of a relative change of particle sizes may be performed by an indirect method, assuming (according to the Reyleigh law [4]) that the fogging of sol is the measure of the increase of particle size and of the possible change of the density of their distribution during coalescence. The turbulence degree may be determined numerically by the intensity of light in the given spectrum range. The amount of light scattered laterally (Tyndall effect) allows us to infer about the system's structure, and the conclusions concerning the nature of dispersed particles, their sizes and shapes my be drawn from the dependence of the light intensity and its polarization on the observation direction and the frequency of the light applied.

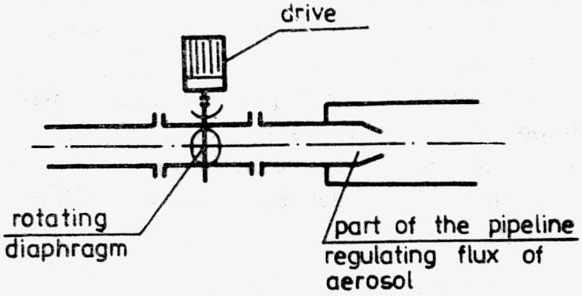
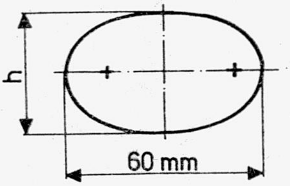


Fig. 4. Generator of disturbances in aerosol flow

Rys. 4. Generator zaburzeń przepływu aerozolu

Symbol	h, mm	A_w/A_c
S1	58	3%
S4	50	16%



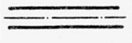
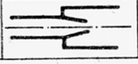
Symbol	Channel type	
K1		diameter ⌀ 60 mm
K3		diameter ⌀ 60/⌀ 80 mm

Fig. 5. Structural variants of pulsation generator

A_w/A_c is the ratio of the area of free cross-section (when the diaphragm covers maximally the pipeline cross-section) to the area of the pipeline cross-section

Rys. 5. Zestawienie wariantów konstrukcyjnych generatora pulsacji

A_w/A_c jest stosunkiem pola przekroju wolnego, kiedy przysłona przesłania maksymalnie przekrój rurociągu, do pola przekroju rurociągu

The intensity of the scattered light was measured by a nephelometer, taking the samples of air with oil mist at the given mass concentrations of 50, 100, and 150 mg/m^3.

In order to simplify the considerations and to interpret qualitatively the results of measurements the following assumptions were made:

intensity of light scattered on a real set of polydispersive particles corresponds to the intensity of light scattered on the set of monodispersive particles of the average linear diameter,

periodic perturbances of the aerosol flux flow do not result in changes of mass concentrations of particles, whereas the changes of the scattered light intensity, measured nephelometrically, bringing the changes in quantitative concentration and sizes of particles, thus are the measure of the coalescence degree,

mass concentrations of particles measured nephelometrically at pulsating aerosol flow are treated as an apparent mass concentration.

Denoting by: d — average linear diameter of particle, s — mass concentration, N — quantitative concentration of particles in gas, ϱ — oil density, and by indices: 1 — quantities referred to undisturbed flow and 2 — quantities referred to pulsation flow, we see that the mass concentration of oil mist, defined as the ratio of oil mass to its unit volume, equals

$$\frac{\pi d_1^3}{6}\varrho N_1 = \frac{\pi d_2^3}{6}\varrho N_2 = s = \mathrm{const} \Rightarrow \frac{d_2}{d_1} = \sqrt[3]{\frac{N_1}{N_2}}. \tag{1}$$

Moreover,

$$\frac{\pi d_1^3}{6}\varrho N_1 = s_1 \tag{2}$$

and

$$\frac{\pi d_1^3}{6}\varrho N_2 = s_1' \tag{3}$$

where s_2' denotes the apparent mass concentration measured nephelometrically at the switched on pulsator.

Dividing eqs. (3) and (2) by sides we get

$$\frac{N_2}{N_1} = \frac{s_2'}{s_1} \tag{4}$$

thus, the relative change of the size (diameter) of particles d_2/d_1 is proportional to

$$\sqrt[3]{s_1/s_2'}.$$

5. RESULTS

Apparent concentration s_2 versus pulsation frequency for various structural variants at the given mass concentrations s is plotted in figs. 6, 7, 8. The results presented show that the pulsation frequencies of flux, i.e. the intensity of its turbulence, affects signi-

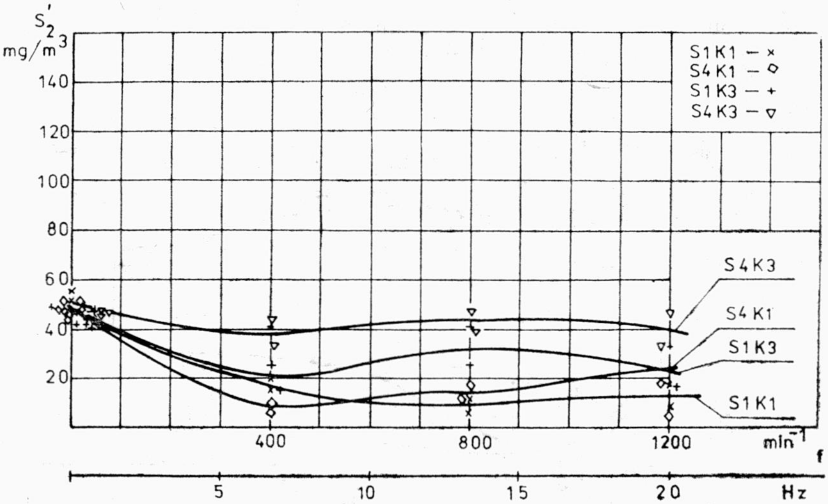


Fig. 6. **Apparent** mass concentration versus frequency of gas flux pulsation ($s = 50$ mg/m^3)

Rys. 6. Zależność pozornej koncentracji masowej od częstotliwości pulsacji strumienia gazu ($s = 50$ mg/m^3)

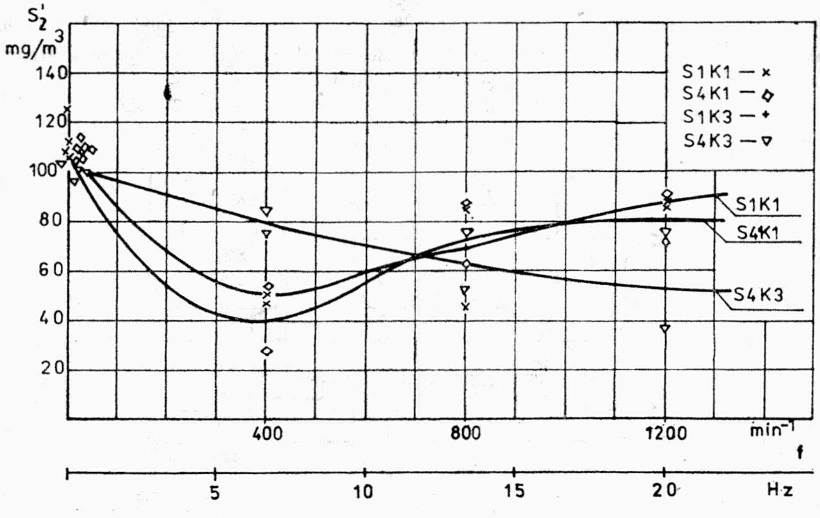


Fig. 7. Apparent mass concentration versus gas flux pulsation frequency ($s = 100$ mg/m^3)

Rys. 7. Zależność wartości pozornej koncentracji masowej od częstotliwości pulsacji strumienia gazu ($s = 100$ mg/m^3)

ficantly the changes of the apparent mass concentration of dispersion phase, being therefore an important factor of the intensification of oil mist coalescence. The coalescence degree of particles depends, moreover, on their initial concentration and on the applied variant of the pulsator structure. It should be noted that the low frequency (5–10Hz) pulsation exerts a most advantageous effect on the course of coalescence process.

Plots shown in figs. 9 and 10 represent relative changes of the average sizes of particles caused by the turbulence of the flowing medium. A distinct effect of pulsation is first of

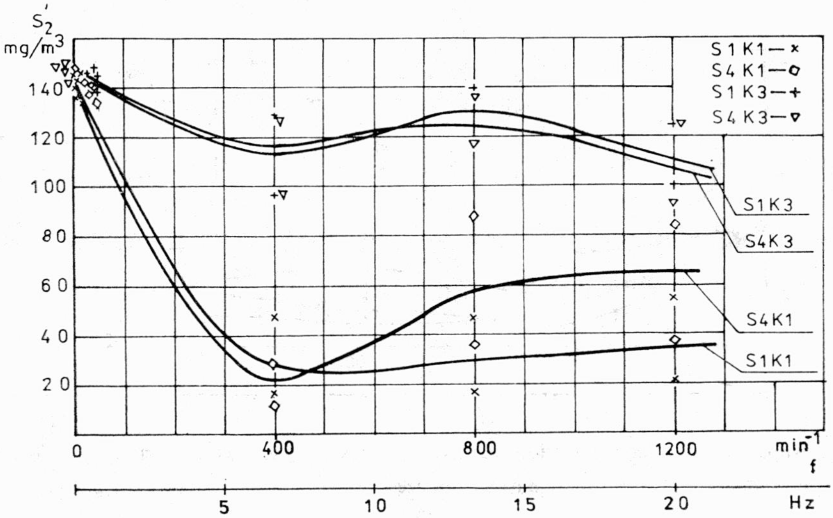


Fig. 8. Apparent mass concentration versus gas flux pulsation frequency ($s = 150$ mg/m^3)

Rys. 8. Zależność wartości pozornej koncentracji masowej od częstotliwości pulsacji strumienia gazu ($s = 150$ mg/m^3)

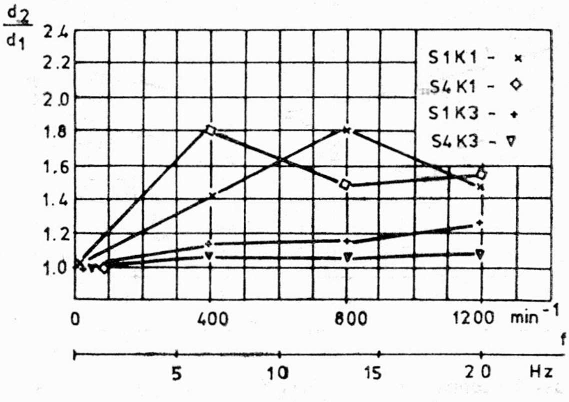


Fig. 9. Relative changes in mean sizes of particles versus gas flux pulsation frequency ($s = 50$ mg/m^3)

Rys. 9. Zależność względnej zmiany średnich wielkości cząstek od częstotliwości pulsacji strumienia gazu ($s = 50$ mg/m^3)

all manifested in quantitative analysis of results of investigations carried out in the structural variant S4K1 in optimal (maximal) regions of turbulence intensities, corresponding to the pulsation frequencies 5–10 Hz; as then the average linear diameter of particles increases maximally.

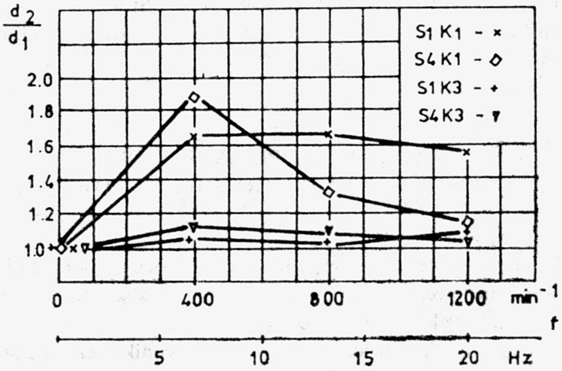


Fig. 10. Relative changes in mean sizes of particles versus gas flux pulsation frequency ($s = 150$ mg/m^3)

Rys. 10. Zależność względnej zmiany średnich wielkości cząstek od częstotliwości pulsacji strumienia gazu ($s = 150$ mg/m^3)

6. CONCLUSIONS

Analysis of coalescence-inducing aeromechanical factors, the results reported in literature [2, 3] on pulsation fluxes and the results of our own investigations allow us to formulate the following conclusions:

the role of entraiment effect may increase if there appear in the aerosol flux the forces directing light particles in the wake of larger particles,

turbulent fluctuations, caused by aerosol flux pulsation, may intensify the perikinetic coalescence,

a substantial decrease of the apparent mass concentration observed in pulsation frequency range (5–10 Hz) corresponds to the increase in the mean linear diameter of particles,

it seems that the intensification of coalescence processes by forcing a non-stationary flux of aerosol, because of a relatively low energy consumption, is one of the most advantageous methods increasing the separation efficiency of particles of liquid aerosols, including those of oil mist.

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KOALESCENCJA KROPEL MGŁY OLEJOWEJ W NIESTACJONARNYM STRUMIENIU POWIETRZA

Przedstawiono mechanizm powstawania mgły olejowej w procesach obróbki mechanicznej oraz scharakteryzowano jej wpływ na bezpieczeństwo i higienę pracy. Wskazano na konieczność poszukiwania nowych rozwiązań, umożliwiających zwiększenie skuteczności separacji drobnodyspersyjnych cząstek aerozoli ciekłych przez wstępną koalescencję. Zanalizowano czynniki aeromechaniczne sprzyjające intensyfikacji koalescencji i przedstawiono koncepcję koalescencji kropel mgły olejowej przez wprowadzenie dwufazowego strumienia (powietrze–krople oleju) w stan pulsacji. Zaprezentowano metodę weryfikacji założeń tej koncepcji. Przytoczono wyniki badań nad koalescencją cząstek mgły olejowej transportowanej przez niestacjonarnie przepływający strumień powietrza o pulsacjach niskiej częstotliwości.

KOALESZENZ VON ÖLTROPFENNEBEL IM NICHTSTATIONÄREN LUFTSTROM

Dargestellt wird der Entstehungsmechanismus von Ölnebel im mechanischen Verarbeitungsprozeß sowie deren Einfluß auf die Arbeitsicherheit. Nötig sind hier neue Lösungen, die eine bessere Separation von Aerosolteilchen hoher Dispersität z. B. durch eine Vorkoaleszenz bewirken sollten. Analysiert wurden aeromechanische Faktoren die die Koaleszenz begünstigen. Dargestellt wird weiter ein Konzept der Koaleszenz von Öltropfennebel durch den Einsatz eines Zweiphasenstrahles (Luft-Öltropfen) im Schwebungszustand. Präsentiert wird ein Wahrheitsbeweis für dieses Konzept. Angeführt werden Ergebnisse der Koaleszenz von Öltropfen; der Transport des Nebels bewirkte ein nichtstationärer Luftstrom der mit niedriger Frequenz pulsierte.

КОАЛЕСЦЕНЦИЯ КАПЕЛЬ МАСЛЯННОГО ТУМАНА В НЕСТАЦИОНАРНОМ ПОТОКЕ ВОЗДУХА

Описан механизм образования маслянного тумана в процессах механической обработки, а также охарактеризовано его влияние на безопасность и гигиену труда. Указана необходимость поиска новых решений, позволяющих повысить эффективность сепарации частиц жидких аэрозолей посредством предварительной коалесценции. Проанализированы аэромеханические факторы, способствующие интенсификации коалесценции и представлена концепция коалесценции капель маслянного тумана путём введения двухфазного потока (воздух–капли масла) в состояние пульсации. Предложен метод верификации основных положений этой концепции. Приведены результаты исследований по коалесценции частиц маслянного тумана, транспортируемого нестационарно протекающим потоком воздуха с пульсацией низкой частоты.