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The investigation of the structure and operation of a multi-channel cyclone, separating fine solid particles from an aggressive dispersed gas and vapour flow

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ABSTRACT

A multi-channel cyclone is a new-generation cleaning device, which purifies a gas flow by removing fine dispersion solid particles of 2 μm and larger in diameter from it. An aggressive dispersed gas flow can be formed under various conditions, for example, in combustion and processing of various products such as drying of chemical compounds, etc., at high temperature and/or high humidity. Multi-channel cyclones of a new generation have a number of advantages over the most widely used equipment for separating the particulate matter from the air flow such as electrostatic and bag filters, which are rather expensive, difficult to maintain and to be used for separating sticky and moist particles from the aggressive gas flow. The paper examines wood and lignin solid particles of different nature and properties present in a gas-vapour flow. Their adhesion and cohesion, depending on the time of the multi-channel cyclone operation aimed at purifying a dusted gas-vapour flow at high gas-vapour temperature and humidity are investigated. The research is aimed at determining the optimal separation efficiency and the aerodynamic parameters of a multi-channel cyclone and their variation by creating an aggressive dispersed gas flow. It assesses the detrimental effect of the deposition of wood and lignin solid particles on its interior surfaces, their cohesion and adhesion and clogging the system. The efficiency of the cyclone's operation is investigated for the flow, moving at medium rates and containing solid particles of various sizes. The highest cyclone's efficiency is determined for its separation of medium- and small-size solid particles. The theoretical study of kinematic and dynamic gas flow viscosity and the calculation of its coefficients as well as the dew point temperature of the flow are performed and the relationships between them are determined. The obtained results are presented and some recommendations for improving the structure of a multi-channel cyclone for separating sticky and moist particles from a humid and hot gas flow are provided.

1. Introduction

In technological processes, taking place at industrial enterprises, the pollutants such as solid particles (SPs) are generated in large amounts. When emitted into the air, they increase the environmental pollution. Usually, these particles are discharged into the closed spaces and pose a threat to human health [1–3].

Effective air purifying devices, including electrostatic and bag filters, are widely used in the world for separating solid particles (particulate matter) from the air. These filters are rather expensive and difficult to use. Besides, their application to separating sticky and moist solid particles is limited and difficult or impossible in the aggressive environment [4,5].

Multi-channel cyclones have semicircular channels, allowing for making closed contours like those of the cyclones having an ordinary hollow structure. Their manufacture is simple and they are easy to install and use [6].

Inside the considered cyclone, there are four elements. Each of these elements (further referred to as curved elements) represents a convex plate, whose outer edge makes a quarter of a circle.

Multi-channel cyclones with the curved elements, making the internal contours, differ from those of a classical cyclone, which does not have any internal elements. A multi-channel cyclone has a relatively simple structure and can be easily installed and operated [5]. Due to the above-mentioned advantages, a multi-channel cyclone-separator is reliable, universal and economical. Closed contours with the spaces between the interior elements allow gas to flow into and out of the channels. A transit flow of gas is filtered many times through the reversible (partially purified) flow of gas and fine solid particles (SPs). This flow is circulating in the spaces between the curved elements. As a

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result of this interaction, larger amounts of SPs are separated and directed to semicircular apertures to drop on the bottom of a hopper [6].

A complex method of gas flow purification based on using filtration and centrifugal separation of particulate matter is a new technology [6–8]. The detailed description of the device for separating dispersed particles from gases or vapours by gravity, inertia, or centrifugal forces is presented as EP Application [9].

The previous results of experimental and theoretical researches provide a knowledge of optimal internal design of multi-channel cyclone, the determination of optimal gas flow velocity into the cyclone's channel and the ratio of peripheral/transit flow distribution in the flow division zones. The performed research of cleaning efficiency in industrial plant under conditions of an aggressive environment [6–12].

A system of curvilinear channels, arranged in some particular order and connected to each other by closed contours, distributes solid particles contained in the polluted gas flow into three groups based on their weight. The particles, whose weight is smaller than a certain critical value, are removed together with a flow of the purified gas. Particles and agglomerates of a larger weight, exceeding the specified values, are returned to the polluted flow or settle in the cyclone's hopper. They get there through semicircular apertures of the outer channels of a cyclone. Particles and agglomerates having the intermediate weight values are distributed among the orbits and circulate in closed contours. A closed contour area is formed of a pair of adjacent channels and the field of the contaminated gas flow or a hopper connected to the cyclone. A six-channel cyclone of this design is able to purify a gas flow from fine dispersion SPs, whose median diameter reaches 5–6 μm, while its purification efficiency is over 80% [11,12].

High relative humidity and temperature are important parameters, which may strongly influence the process of gas flow purification in various branches of industry. The influence of these parameters and their assessment are particularly relevant for the processes taking place in chemical and building materials' industries, as well as in agriculture, food industry, power engineering, ventilation and air conditioning [13]. Using a multi-channel cyclone is complicated for purifying a gas flow under specific conditions, i.e. at high humidity (95% and higher) and high temperature (up to 200 °C). The application of this cleaning device for separating solid particles from an aggressive gas flow requires the improvement of its geometry.

An aggressive gas flow may be formed due to the influence of a number of natural or artificial, physical, chemical and other phenomena or processes. They can produce the environment independent of the aggregate state which negatively affects technological processes, materials and equipment so that they cannot be used according to their functions [14] or cause the failure of machines and devices.

These environmental conditions are not only unfavourable to the implementation of technological processes and harmful to human health, but may be dangerous to technological equipment because of the risk of its possible explosion or ignition [15,16]. In the most widely used multi-channel cyclones, the uniformity of purifying gas flows from SPs is based on the interaction between the SPs and the interior cyclone's surfaces restricting the flows. The accumulated particles form sediment layers on the surfaces, which have an influence on the cyclone's operation and change the movement of the flow. They also produce a negative effect on the mechanism of particle deposition, which decreases the efficiency of a cyclone's operation [17–19].

A gas flow with a certain amount of water vapour found in the gaseous phase is characterized by partial pressure, which is not higher than the saturated vapour pressure under particular gas–vapour–fog flow conditions. The water vapour in a gas flow reduces its density, since the molar mass of water is smaller (18 g/mol) than that of a dry gas flow (29 g/mol). A humid gas–vapour–fog flow may be considered a mixture of ideal gases, where the density of every component allows for obtaining the required density of a mixture [20].

Water vapour condensation on the surface of fine dispersion SPs and fog can be observed in the case of aggressive water vapour of high humidity and the gas flow of high temperature. The elasticity of vapour on a convex surface is higher than vapour elasticity on a smooth surface, since the latter is higher than the elasticity on the concave surface [21]. Therefore, vapour condenses more intensively on fine dispersion solid particles of the irregular form. This is true for real particles, whose surfaces are concave, rather than for the particles with the convex surfaces. If vapour pressure on the smooth surface of a liquid is denoted by p_0, then, vapour pressure of a fine dispersion SP, whose diameter is d, can be calculated by Eq. (1):

$$\rho_0 \frac{RT}{M} \ln \frac{p}{p_0} = \frac{4\sigma_0}{d} \tag{1}$$

where ρ_0 is the fluid density, g/cm^3; p is saturation pressure on the particle's surface, kg/cm^3; σ is the fluid surface strength, when temperature is expressed by (°K·g)/s^2; M is molecular mass; p_0 is saturation pressure, when temperature is T in °K, kg/cm^2.

Based on this equation, it may be stated that when the cross-section of a fine dispersion SP is reduced, the pressure of vapour on its surface is increased. This means that a liquid evaporates more easily and complicates the condensation of water vapour [22].

Water vapour gets into a dispersed gas flow from the processing equipment, e.g. condensers, dryers and autoclaves, during various production processes, using solvents such as water [23]. Under the temperatures approaching the boiling temperatures of these solvents, a dispersed gas flow gets into the cleaning equipment as a gas–vapour mixture. When machines and devices cool down and reach the dew point temperature, a gas-vapour-fog mixture is formed, while the solvent is condensed on the cooler surfaces of devices during thermophoresis [24].

When water is evaporating from the surface, a great amount of heat energy is used, and when it is condensing, the same heat is released into the air. It implies that a vapour–fog flow also has an influence on the energy balance.

Montazeri et al. [25] have used a well-known approximation, which can be applied to calculating the dew point temperature (Tdp) by determining gas temperature taken by a dry thermometer (T) and relative humidity (RH) from Eqs. (2) and (3) (Magnus formulas):

$$\gamma(T,RH) = \ln\left(\frac{RH}{100}\right) + \frac{bT}{c+T}; \tag{2}$$

$$T_{dp} = \frac{c\nu(T,RH)}{b-\nu(T,RH)}, \tag{3}$$

where ρ_0 is the fluid density, g/cm^3; p is saturation pressure on the particle surface, kg/cm^3; σ is the fluid surface strength, when temperature is expressed by (°K·g)/s^2; M is molecular mass; p_0 is saturation pressure, when temperature is T in °K, kg/cm^2.

A simple approximation allows for calculating the dew point temperature to an accuracy of ±1 °C, when the relative humidity is above 50% (Eq. (4)) [26]:

$$T_{dp} \approx T - \frac{100-RH}{5}; RH \approx 100-5(T-T_{dp}). \tag{4}$$

It can be seen from this equation that for every 1 °C difference between the dew point and gas temperature taken by a dry thermometer, the relative humidity is reduced by 5%, starting the deduction from 100%, when the gas temperatures of the dew point and the temperatures taken by a dry thermometer are equal.

The goal of the present research is to determine the aerodynamic parameters of the dispersed flow of aggressive gas-vapour-fog dispersed flow and their variation. Moreover, the aim is to describe the adhesion of wood and lignin SPs and its impact on the operation of a multi-channel cyclone, when the apertures of the device are clogged, and to find the best solution to upgrading the cyclone's