NEW CONCEPT OF IN/OUT AIR QUALITY CONTROL IN LIVESTOCK BUILDINGS

by

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The object of this research is the new concept of the original universal system for air quality and energy control in laboratory conditions (wet scrubbing system) based on the „clean air in/out" principle. Namely, the process involves a partial or complete exchange of recirculated treated air. From the aspect of water, as a pure medium, the system is characterized by broad application in the open, semi-open, and closed air treatment systems: primarily in the breeding and accompanying agricultural facilities, industrial, cultural, sports, tourist, medical and other controlled spaces. The analysis showed that the system at its inlet unit and with the block structure and logical phase development, proved energy, environmental and qualitative efficiency in the removal of PM10 and PM2.5 particles from the controlled dust doses in laboratory air. The measurements of PM10 and PM2.5 concentrations were performed with two Alphasense OPC-N3 optical counters at the inlet and outlet of the system. Five operating regimes with frequency regulated number of revolutions of the turbo elements that was taken as an independent variable, achieved different degrees of removal of PM10 and PM2.5 from the treated laboratory air: 97.70-98.53% and 62.19-75.75%, respectively. The assessment of system energy use was done by parallel measuring of electric power and comparative deviations of its absolute values in the first decimal. Energy consumption for the treatment of $1m^3$ of air ranged from 0.00011-0.00016 kWm^{-3}. Statistical analysis of qualitative indicators revealed significant differences between the operating regimes and the obtained values.

Keywords: *air quality, PM, wet purification, ventilation, livestock, energy*

Introduction

Optimal breeding environment is a significant factor for the improvement of qualitative, productive, energy, and environmental efficiency of adequate breeding cycle in livestock [1]. The quality of breeding environment is determined by the effects of variables such as

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temperature, humidity and air velocity, ventilation rate, concentration of dust, gases and microorganisms [2, 3]. There is a clear tendency of technical and technological advancements to increase the livestock production efficiency in closed high-density breeding facilities, which has proved to cause an extreme increase in the environmental pollution of such facilities with dust, gases, microbes, and germs, thus posing a health risk to the breeding units and humans [4]. Particulate matter (PM) is an important factor in the pollution of ambient air and air on animal farms as it represents a complex mixture of solid and liquid materials, including parts of dry hay used as feed or bedding, grains, concentrated nutrients, animal skin, hair, digestive tract products, and microorganisms mostly of organic origin [5, 6]. They absorb unpleasant odors, carry pathogens, endotoxins, gases and liquid substances [7-9]. Animal species, type of breeding, density, diet, air treatment strategy, season, and time of day are the key factors of PM concentrations in the breeding facilities [10]. Comparison of their concentrations shows the extremes with respect to different farm animals: poultry, pigs and cattle [11]. In the zone of the breeders' respiratory system, during regular operations, the concentration of PM in livestock facilities varies between 0.2-480 $\mathrm{mgm^{-3}}$ [12], and the activity of animals during feeding time causes the extreme values [13-15]. Negative consequences of that are the input/output ratio of the breeding cycle, the quality of the principal product, the health and well-being of the breeders, the condition of facilities and the accompanying equipment, ecological consequences on immediate living environment, *etc*.

Although the mechanisms of the influence of type and concentration of PM on human health have been unjustifiably under investigated, there is a consequential relation between inhaled particles, both fine PM2.5 and coarse PM 2.5-PM10, and respiratory and cardiovascular diseases which result in mortality [16-19]. Rapid deterioration of mechanical components of the structure, as well as the accompanying technical and technological equipment in livestock facilities, is the consequence of high concentrations of PM in them [20-22]. Laws on environmental protection and accompanying regulations in some countries indicate the importance of air quality in terms of the impact of PM content on local and global living environments [18]. Simple ventilation in livestock facilities releases polluted air directly into the local ecosystem [23], thus negatively affecting its structural units, primarily the vegetation stress [24], which implies an obligatory controlled reduction of PM concentrations [25].

At a global scale, the nature of the problem and the relative market relations of input/output breeding processes in livestock are characterized by reduced application of technical and technological procedures for air quality control in the breeding facilities. Today, a group of technical and technological measures for PM control in livestock facilities includes ventilation, preventive internal control of pollutant sources, reduction of gaseous component and dust emissions in the ecosystem-biofilters and purification technologies: dry and wet filters, electrostatic filters, ionizers, *etc*. [11, 26]. End-of-pipe air purification does not improve the quality of the ambient, but it significantly reduces the concentration of PM in the immediate environment [27-30]. Diversity of breeding systems, requirements of animal species depending on their type, breed and age, regional climatic conditions, and energy requirements, are just some of the reasons for the lack of a generally efficient and sustainable global strategy for air quality control in livestock breeding. The most influential factor of the aforementioned is the energy, as the estimated energy of farming is approximately 6 EJ $\mathrm{year^{-1}}$, which is about 1.2% of total world consumption [31]. A significant share of this energy is spent on the maintenance of microclimatic conditions in broiler breeding, with electricity and heating shares being 75.5% and 96.3%, respectively [32]. Thermal and qualitative potentials of indoor/outdoor air require a number of preset air exchanges. According to empirical formulas, which are based on the assumption of a uniform ambient distribution of temperature, humidity and air pollutants, there are ventilation rates ranging from 2-60 exchanges per hour [33]. The heat stress in the US has been causing annual losses in the dairy industry estimated at 1.69-2.36 billion dollars, which indicates the importance of the control of energy requirements in facilities for livestock breeding [34].

Laboratory for Agricultural Engineering in Animal Husbandry, Department of Agricultural Engineering, Faculty of Agriculture, University of Novi Sad, Novi Sad, Serbia, has been involved in the integral development of an original wet scrubbing system (WSS) and its energy control in order to reduce environmental, energy and quality problems relating to animal breeding. The reason why we chose to work with and develop wet scrubbers is that they can also be used to remove gases such as ammonia and *etc*. The results of analysis of this block structure, which offers the possibilities of partial and combined operations in the process of air purification and conditioning, are presented only for the inlet unit of the WSS. As regards the ambient dust content, the system is based on the concept of *clean input/output*. Namely, when the indoor air is exchanged with the outdoor air, the input air is purified and the output, which is formally clean due to its qualitative composition, is released. In the exchange interval, the ambient air is recirculated and treated in terms of condition and quality, and the exchange cycle is determined by the concentration of oxygen in it. Of course, that air purification with wet scrubbers has its limitations and disadvantages. The presence of water tends to increase the degree of corrosion as well as the formation of biological PM, and during cold weather problems with freezing occur. Also waste water requires additional treatment [11].

The WSS represents the *limit value* of the mentioned form of generally efficient and sustainable global strategy for air quality control, both in livestock breeding, and in any other segment of human activity. The objective of this paper was to define the degree of qualitative environmental and energy efficiency of the WSS inlet unit during the removal of PM2.5 and PM10 dust particles from the air in the laboratory environment.

Material and methods

The WSS inlet unit

Figure 1 shows a 3-D model of a laboratory prototype of WSS with the marked position of the analyzed inlet unit – I. Axial rotors distribute the treated air along the closed recirculation path - axial fan – 3 - axial recirculation fan – 4 - automatically adjustable *air dumper* – 5 - water atomizing rotor R1 – 1, water atomizing rotor R2 – 2 - axial fan – 3. Modified forms of radial rotors, R1 and R2 atomizing rotors, under the influence of centrifugal force and water jet dispersion performed by it, undesirable dust particles get separated from the treated air. The automatic valve enables partial or complete recirculation of indoor air, *i.e.* exchange-ventilation of the outdoor air. The input of recirculating air-flow from the laboratory environment for additional treatment with controlled dosing of dust from the selected source is performed by two axial fans presented in fig. 2. Used dust originates from concentrated animal feed.

The experiment setup

Measurement of dust concentration in laboratory air was performed with two optical particle counters *Alphasense* OPC-N3 with a measuring range for particle sizes from 0.35 to 40 μm, at the inlet and outlet of WSS, fig. 2. The manufacturer offers a comparison of the

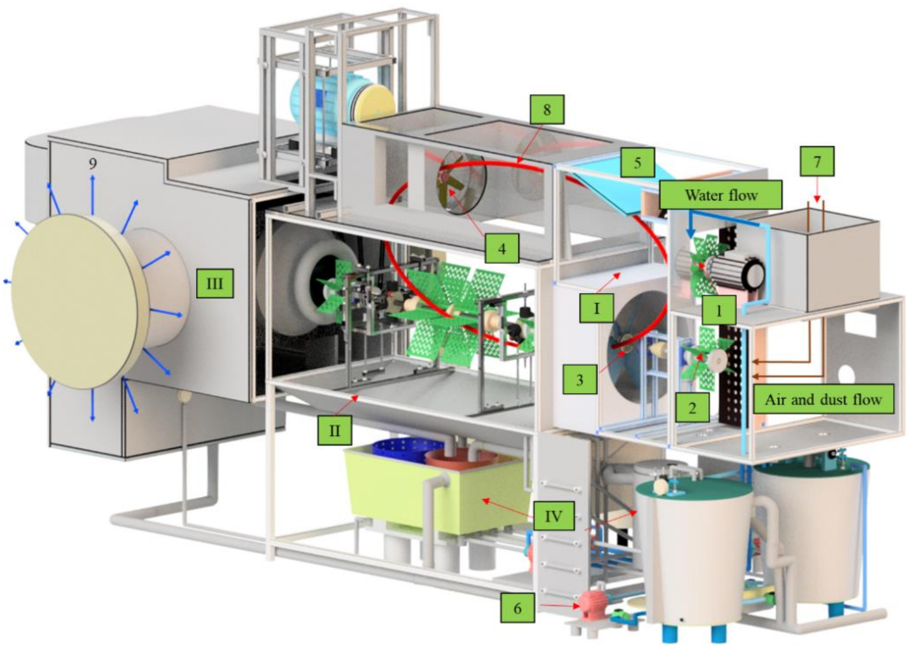

Figure 1. The 3D model of a laboratory prototype of WSS;
I – inlet unit, II – central unit, III – exiting unit, IV – water distribution and filtration unit, 1 –atomizing rotor R1, 2 – atomizing rotor R2, 3 – axial fan, 4 – axial fan of the recirculating channel, 5 – automatic adjustable air dumper, 6 – pump, 7 – air inlet, 8 – air recirculation, and 9 – air outlet

sensor with reference devices for measuring concentrations, but there is no exact data on the relative error. Namely, the ambient air was forced into the first unit of the WSS, through a channel, by two axial fans connected in a series circuit with adjustable flow via a voltage regulator, fig. 2. Under neutral pressure, between the two fans, the dust was dosed pneumatically from a mixture of concentrated organic feed and inorganic sand dust in a specially adapted PVC chamber. An instrument for measuring the dust concentration in the input was installed on 2/3 of the channel, fig. 3, – 1. Another particle counter was installed at the WSS outlet, fig. 3 – 2 to determine the degree of removal of PM10 and PM2.5. The air treated at the outlet is under adequate overpressure, which ensures the efficiency of removal of PM10 and PM2.5 without the influence of the immediate environment. Efficiency was calculated as the quotient of the input/output concentration difference and input concentration, eq. 1 [35]:

$$R = \frac{C_\mathrm{i} - C_\mathrm{o}}{C_\mathrm{i}} 100\% \tag{1}$$

where C_i and C_o are concentrations at inlet and outlet of WSS.

Figure 2 shows a scheme of the measuring point of the instrument. The inlet unit of WSS consists of:

– Water atomizing rotor R1 mounted directly on a three-phase electric motor shaft with power of 1.1 kW, controlled by a frequency regulator, with a display showing the currently engaged power for five operating regimes - speeds, min^{-1}, *i.e.* frequency: 15 Hz, 20 Hz, 25 Hz, 30 Hz, and 35 Hz, respectively. The number of revolutions was read from the frequency regulator display and verified stroboscopically.

- Water atomizing rotor R2- on a joint shaft with the rotor of the intake-recirculating axial fan driven by a three-phase electric motor of rated power 1.1 kW via double pulley. The electric motor was controlled by a frequency regulator when measuring a constant number of revolutions in min^{-1}, *i.e.* constant frequency of 30 Hz. The air-flow was 6987 m^3 per hours.
- Axial fan in the recirculation channel mounted directly on the shaft of a 170 W single-phase electric motor controlled by a voltage regulator.

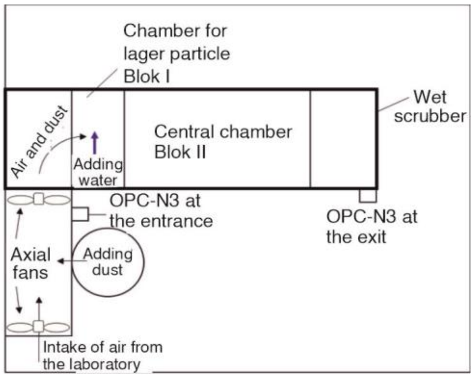

Figure 2. The instrument set

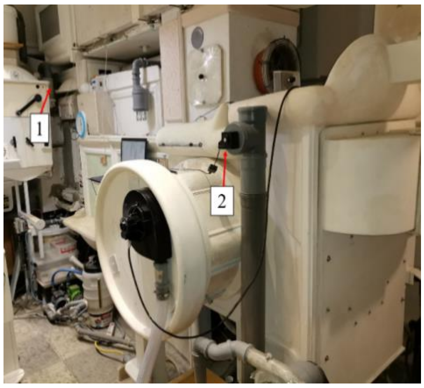

Figure 3. A laboratory prototype of WSS with the position of measuring instruments

Automatically stored and changeable clean water from the city distribution network is delivered from suitable storage PVC containers on the front side of R1 atomizing rotor via a single-phase electric motor pump of rated power 0.24 kW. Adjustable recirculation water flow was kept constant at 1.25 $l\cdot min^{-1}$. Consumption of effective electric power (kWh) by the working parts of the system was measured by the corresponding electric meters connected in series to the reference meter, with additional verification by a digital meter with measuring accuracy of ±1% (±0.2 W) for engaged power. The engaged engine power in all operating regimes of R1 atomizing rotor was measured in idle mode, with and without the water inflow. The engaged reactive energy was measured by a reference meter. Due to the very low energy consumption, it was not possible to accurately measure the share of reactive energy for individual treatments, and for that reason it was calculated for all treatments collectively.

One-way ANOVA with frequency as an independent variable was used for statistical analysis, due to need to determine the existence of statistically significant differences among the five operating regimes. All operating regimes (treatments, further in the text) were repeated 20 times. Differences between the treatments were tested by LSD (Least Significant Difference) test ($P < 0.01$). All statistical analyses were done in Microsoft Excel 2013.

Results and discussion

The efficiency of removal of PM10 and PM2.5

The numbers of revolutions of the R1 atomizing rotor for the following frequencies 15 Hz, 20 Hz, 25 Hz, 30 Hz, and 35 Hz were 880 min^{-1}, 1166 min^{-1}, 1450 min^{-1}, 1733 min^{-1}, and 2014 min^{-1}, respectively. The measured concentrations of PM10 and PM2.5 at inlet and outlet of the WSS for all five treatments are presented in fig. 4.

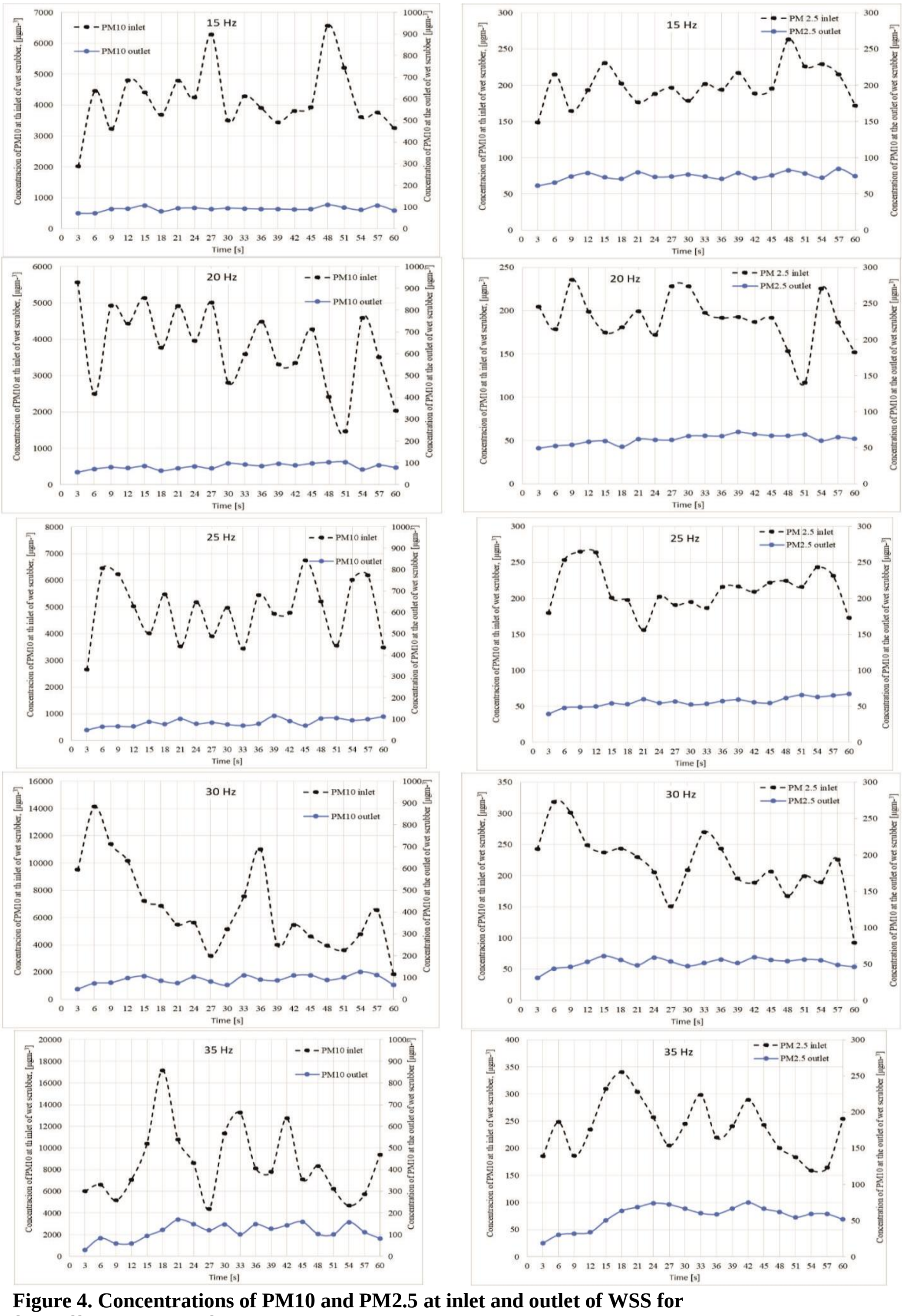

Figure 4. Concentrations of PM10 and PM2.5 at inlet and outlet of WSS for five different speeds of the R1 atomizing rotor

The average concentrations of PM10 and PM2.5, measured at the WSS inlet and outlet, for the given frequencies, are presented in tab. 1. Table 1 also shows the efficiency of removal. Figure 5 shows efficiency of removal of PM10 and PM2.5 with respect to R1 atomizing rotor speed.

Table 1. Average concentrations of PM10 and PM2.5 with the efficiency of removal

	PM10			PM2.5		
Treatment	Inlet concentration [μgm^{-3}]	Outlet concentration [μgm^{-3}]	Efficiency of removal [%]	Inlet concentration [μgm^{-3}]	Outlet concentration [μgm^{-3}]	Efficiency of removal [%]
I	3997.89	88.18	97.70	192.09	71.68	62.19
II	3701.59	80.70	97.46	183.28	59.73	66.43
III	4680.42	79.97	98.15	204.76	53.84	73.08
IV	6515.88	88.93	98.29	215.25	50.86	74.63
V	8076.32	111.27	98.53	227.62	55.44	75.75

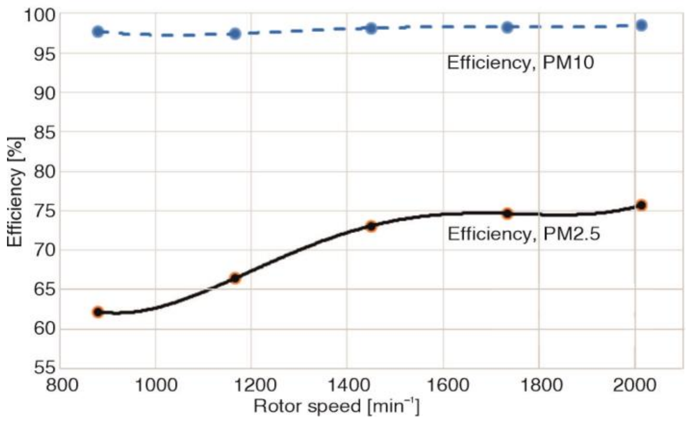

Figure 5. Efficiency of removal of PM10 and PM2.5 with respect to R1 atomizing rotor speed

The results obtained are approximately consistent with the study of Zhao *et al.* [35] whose scrubber efficiency for PM10 removal ranged from 61-93%, and for PM2.5, from 47-90% at flow values from 8775 to 29000 m^3h^{-1}.

The ANOVA test showed that it was possible to group the operating regimes for the tested values of PM10 and PM2.5 to 15 and 20 Hz, and 25 Hz, 30 Hz, and 35 Hz. There is no statistically significant difference between the regimes of these groups, but there is a difference between the groups. Thus, by increasing the speed of the rotor R1 to 1450 min^{-1}, the efficiency of removal of PM10 and PM2.5 increased. Further increase in the number of revolutions gave a significant decrease in the efficiency of PM10 and PM2.5 removal. Naturally, higher boundary velocity of the vanes resulted in a more intensive dispersion of the jet, as well as the increased, but only partially used effect of the centrifugal force of the perforated wings of the atomizing rotor on the removed dust particles.

It is worth mentioning that, in the course of logical WSS development, yet on the line of the conflict between subjectively intuitive and realistic, the presented results significantly deviate from the possible ones, which are significantly more efficient. Namely, the predicted experiential effect of the centrifugal force on the absolute values of the presented results is marginalized by the dispersion effects of the working medium. The subsequent development and measurement steps, with slight modifications of the recirculation and line flows of the treated air in the WSS will significantly intensify the centrifugal force phenomenon.

Energy efficiency

Table 2 shows total power consumption of the R1 atomizing rotor, a percentage share with electric motor idling, the rotation of the atomizing rotor with and without water.

Table 2. The R1 atomizing rotor power consumption

Frequency [Hz]	15	20	25	30	35
Engaged power [W]	40	90	150	230	350
Percentage portion for idle mode [%]	75	44	33	26	20
Percentage portion for R1 – no water [%]	25	44	60	69	77
Percentage portion of R1 with water [%]	0	11	7	5	3

The effective energy of purification has a quarter share, *i.e.* 25% for minimum atomizing rotor speed, up to 80% for the maximum speed. Obviously, more energy-efficient regimes are related to higher frequency intervals, that is, intensive spray treatments of the working medium in interaction with air as the object of purification. Figure 6 shows the energy engaged for the operation of the R1 atomizing rotor during different operating regimes. The engaged power at 30 Hz for the operation of the R2 atomizing rotor and the axial fan was 350 W. The number of realized rotations of the electric motor was 579 min^{-1}, and the shaft with rotor and axial fan was 1009 min^{-1}, which indicated the transmission ratio of 0.57, so the unjustifiable slipping of 4.1% was subsequently eliminated. The power engaged to drive the axial fan of the recirculation channel was 170 W, and the speed was 843 min^{-1}. The engaging power during parallel operation of the elements for individual treatments was: 800 W, 850 W, 910 W, 990 W, and 1110 W, respectively. The total share of reactive power for the determined electric power consumption during all treatments was 16.67%. Energy consumption for 1m^3 of purified air was 0.00011 $kWhm^{-3}$, 0.00012 $kWhm^{-3}$, 0.00013 $kWhm^{-3}$, 0.00014 $kWhm^{-3}$, and 0.00016 $kWhm^{-3}$ for different treatments.

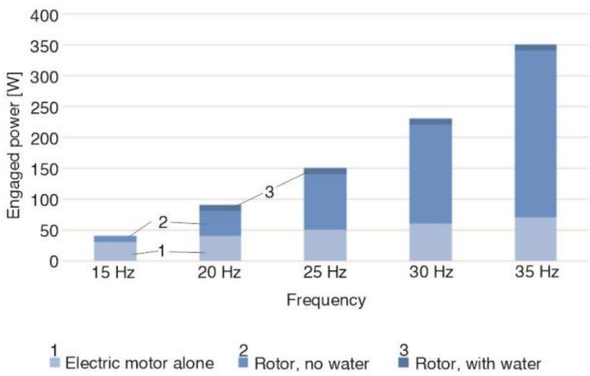

Figure 6. Engaged power with different treatments

In order to obtain valid values, it is highly recommended that at least one additional independent procedure is conducted, with the experiential adoption of a more realistic one in case of significant deviations. With fans run by three-phase electric motors, it is necessary to reduce the reactive energy from the distribution system by installing an adequate capacitor battery, which can reduce the consumption of effective electric power. A further course of research would include numerous tests of the entire WSS: separate and combined operation of its units, multiplication of centrifugal force, application of collision and impulse theory, combinations of shape, material and size of atomizing rotor vanes, application of electrostatics, magnetic field, heat pump effects and a series of proven natural phenomena, with the aim of developing solutions in the form of the limits of a sustainable global strategy for air quality control, both in animal husbandry and in any segment of human activity.

Conclusions

The goal was to determine the efficiency of capturing PM10 and PM 2.5 from the air in laboratory conditions of the WSS inlet unit, as well as determining the energy required for the mentioned process. The capturing efficiency was 97.46-98.53% and 62.19-75.75% for PM10 and PM2.5, respectively. Energy consumption for $1m^3$ of purified air was in range 0.00011-0.00016 $kWhm^{-3}$.

The main principle of the application of the WSS and conditioning of the ambient air in livestock breeding facilities, is *clean input/output air*. The limiting factor for its exchange during cyclic recirculation in a closed or semi-open space is primarily the concentration of oxygen. Future research will include the entire system, all units, so an increase in capturing efficiency, especially of smaller PM2.5 particles, is expected. It is also planned to implement a heat pump, where significant energy savings are expected, especially in winter and summer. The system provides upgrading with chemical, mechanical and electrical principles for reducing potential gaseous components, such as vapors from digestive and respiratory tract, and potentially pathogenic micro world.

Of particular importance is the verification of measured values by using at least two independent methods, or instruments of the same type but of different origin, to meet the complexity of their precise measurement procedures.

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Nomenclature

WSS – wet scrubbing system
R – purification efficiency
C_i – PM concentration at inlet
C_o – PM concentration at outlet

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