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DESIGN AND PERFORMANCE OF A CYCLONE SEPARATOR INTEGRATED WITH HEAT EXCHANGER FOR SMOKED FISH PRODUCTION

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ABSTRACT

This paper presents the design and performance characteristics of a cyclone separator used in smoked fish processing. The application of cyclone in smoked fish processing was intended to reduce contaminants such as char, ash, soot, and a fraction of tar with its polycyclic aromatic hydrocarbon (PAH) compound in the smoked fish. These contaminants potentially decrease both product quality and safety of smoked fish. The cyclone used was designed according to high-efficiency Stairmand's cyclone to separate solid particles from the smoke-air stream. A centrifugal blower of the cyclone, which was integrated with a heat exchanger, generated a forced smoke-air stream of the indirect smokehouse. The collection efficiency of the cyclone was 94.7%, which was higher than the prediction of 93.3%. Visual observation found that tar was trapped and sticky at the inside surface of the cyclone and the dust bin. The reduction of these contaminants contributed to the decrease of the PAH compound, which was indicated by low benzo(a)pyrene content (below the maximum level of Turkish food codex for 2.0 μg/kg). The total pressure drop of the cyclone was 204 Pa, which was lower than the predicted value of 332 Pa. The ratio of energy consumed to pressure drop for the cyclone separator was 22.6 MJ/Pa.

Keywords: smokehouse, fly ash, collection efficiency, benzo (a) pyrene, solid particles.

INTRODUCTION

Smokehouse in this study was intended to process fish into processed products with smoke flavour. This method of processing has been known for a long time and had evolved since the beginning of human civilisation. Smoking techniques based on smoke temperature can be divided into cold smoking (12-25 ^{o}C), warm smoking (25-45 ^{o}C) and hot smoking (40-90 ^{o}C) [28]. Principally, smoking process is done by burning biomass materials in a burning chamber which generate smokes. Smokehouses can be grouped into three types based on smoke-air stream; i.e. (1) natural air circulation, (2) air-conditioned or forced air, and (3) continuous. Modifications of these three types can be found anywhere in our surrounding but the trends of the air-conditioned or forced-ventilation smokehouses have largely replaced the natural-air type [1].

Smoke from biomass consists of components such as gases, liquid, and solid particles. Most of the smoke is air with a mixture of small particles of different sizes. The smoke contains mostly particle which diameters less than 2.5 μm, with the greatest concentration of < 0.12 μm [14]. Meanwhile, the Codex Alimentarius Commission state that particles in the smoke had the size of 0.2-0.4 μm generally or as low as 0.05 to 1 μm, and estimated to constitute 90% of its overall weight [2]. In addition, smoke produced from biomass combustion contains components of char, ash, soot and tar fraction. Tar according to Sreelal (2015) is a by-product of a combustion process that commonly produced by a gasifier. This by-product is formed when the mass of wood or other biomass material is converted into flammable gases with some ash and charcoal residue. Tar could be in the form of a liquid, and mixed with flammable gases include methane (and other simple gaseous hydrocarbons), hydrogen and carbon monoxide [31]. All forms of the solid particles have commonly become a contaminant in processed fish, especially for forced convection smokehouse. Several methods such as settling chamber, cyclone separator, liquid scrubbers, filters and electrostatic precipitators can be used to overcome the contaminating solid particles in the smoking process [4]. Settling chamber is probably the simplest and the earliest type while cyclone separator is one of the most widely used in dust-collection equipment [22].

The biomass material burned in this study to generate smoke was coconut shell. The coconut shell was chosen because of its relatively high heating value. The high heating value was required to achieve temperature generally used in the hot smoking method. The coconut shell also contains higher combustible matter and lower ash content than other biomass such as rice straw and sugarcane bagasse [32].

Solid particles resulted from biomass burning mostly fly ash can become a contaminant in the fish smoking process unless they are handled appropriately. The fly ash from biomass burning is also recognised as a major source of ultrafine particles that can cause undesirable effects when inhaled. These effects can include cardiovascular and pulmonary diseases as well as lung cancer [15, 23]. The results reported in the literature show that the size of biomass fly ash particles varies from

0.01- 0.05 μm up to more than 1-2 mm, but these materials are usually excellent as their median size, which dominant below 10 - 100 μm [18, 35]. Particle density of biomass ash varies between about 2180 and 2750 kg/m^3 [11], and up to 3021 kg/m^3 [35]. The values of particle density indicated previously are for ash particles from the combustions of wheat straw and wood kinds. A lower value of particle density is found on ash particle from coconut shell (2050 kg/m^3) [16]. The bulk density of biomass fly ash were mostly between 101 - 830 kg/m^3 (mean 392 kg/m^3) [9, 35], and up to 960 kg/m^3 [34].

Design aspects of a smokehouse evolved from traditional to a modern system that presents novelties such as of directly smoking or indirectly, natural or forced air circulation and structural design of smoking chamber and smoke box separately or non-separated. There is not a milestone to indicate when the innovation of smokehouse has been begun, but there have been modifications of design system since 1939. The Torry kiln smokehouse (Scotland) known as the first smoking device in smoking history and brought a revolution in the industry of fishing [39]. Since that, the design of the smokehouse was developed in various models according to local custom. In Ghana, modifications of the fish smoking oven with innovation are the oven types introduced by Adjetey (1962) and Chorkor (1970) [7]. The oven type of Adjetey had the separate smoke box and smoke chamber, chimney, and fish trays. Meanwhile, the Chorkor type had good smoking conditions, used traditional materials, easy handling (trays), fuel efficiency and healthier operation. Other types of the fish smoking kiln are those from Nigeria, Ghana, and Indonesia. The fish-smoking kiln designed in Nigeria had three layers; stainless steel, glass fibre as insulation and mild steel for the peripheral walls. The design was addressed to make enclosed kiln to uniformly smoked fish under hot smoking temperature or above (120-200 ^{o}C) from sawdust and maize cob as fuels [20]. In a recent modification from Ghana, the traditional oven was equipped with a removable filter filled with activated charcoal to reduce PAH contamination. This system used natural-air circulation with the wood burning chamber and the smoking chamber separated by a removable filter [5]. The oven type from Indonesia is a smoking cabinet with a vertical array of trays. In this system, the smoke box is set up at the bottom with upward natural-air circulation. The smoking chamber and the smoke box are separated only by a wire mesh [24].

Among the smokehouses described previously, none has been designed to overcome residuals of biomass burning (char, ash, dust, soot, and tar), especially for the forced smoke-air stream smokehouse. Hence, it is important to design an indirect smoking, which separates the smoking chamber from the biomass-burning chamber with a device to separate contaminants from biomass-burning residuals. The objective of this study was to design and test the performance of an integrated cyclone separator with a heat exchanger as the smoke-heat generator. The cyclone separator designed in this study was equipped with a centrifugal blower intended to separate solid particles from the smoke-air stream. Meanwhile, the shell structure with baffles of the heat exchanger aims to hold up the tar and fine fraction of ash or dust that pass through the cyclone.

MATERIALS AND METHODS

Cyclone separator

The cyclone separator was designed according to high-efficiency Stairmand's cyclone. The scale of cyclone dimension is as Table-1.

Table-1. Dimension of the cyclone.

Cyclone geometry	Scale
(1)	**(2)**
Diameter (D)	D
Height of inlet (a)	0,5*D
Width of inlet (b)	0,25*D
Diameter of outlet (do)	0,5*D
Diameter of dust outlet (Bc)	0,375*D
Length of cyclone body (h)	1,5*D
Length of cyclone cone (hc)	2,5*D
Total length (H)	4*D

The standard design for high-efficiency cyclone have characteristics; 0.203 m in diameter, flow rate (Q_1) 223 m^3/h, solid-fluid density difference ($\Delta\rho_1$) 2000 kg/m^3 and test fluid viscosity air at 1 atm, 20 ^{o}C (μ_1) 1.81x10^{-5} N.s/m^2.

The design of cyclone is assumed to operate on temperature approximation of 100 ^{o}C (fluid viscosity, μ_2 = 2.1x10^{-5} N.s/m^2), solid-fluid density difference is equal to ($\Delta\rho_2$) 2050 kg/m^3. The centrifugal blower with flow rate 282 m^3/h and static pressure of 0.65 kPa will drive the cyclone separator. It is recommended the minimum gas velocity for the conveying velocities in the pipe that are dependent upon the nature of the contaminant. Gas velocities for the contaminant close to the smoke/fumes/very light dust were about 10 m/s, 15 m/s for dry medium density dust (sawdust, grain) and 25 m/s for heavy dust (metal turnings) [10].

In addition, the design of cyclone separator was also based on the particle size distribution of ash/dust from the wall of the chimney as presented in Table-2 column (1) and (2). In the same Table-2 on column (3) and (4), particle size distribution from cyclone separator testing is presented as materials to be analyzed. The particle size distributions of both sources are presented in Table-2.

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Table-2. Particles size distribution, PSD.

Particles size, μm	Pre-design, % weight less than	Particles size, μm	After-design, % weight less than
(1)	(2)	(3)	(4)
50	84.83	80	73.54
40	73.49	56	52.12
28	54.17	38	33.92
20	37.44	20	18.57
10	13.85	10	9.02
5	5.21	5	4.56
2	1.61	2	1.6

The calculation and conversion use technical equation (1) - (2) below:

$$A_i = \frac{Q_{blower}}{v_i} \quad (1)$$

$$a*b = 0.5D*0.25D = 0.125D^2 = A_i \quad (2)$$

Then the diameter of the cyclone was found, D = 0.25 m and the entire cyclone dimension in scale as in Table-1. We could predict the efficiency of the cyclone separator design based on particles that had been brushed from the chimney. The prediction of efficiency was also based on performance curve of the high-efficiency cyclone. As we note C1 and C2 is a subscript for cyclone separator standard and cyclone separator designed respectively, the following equation (3) is used to transform and obtain scaling factor (d_2) [30].

$$d_2 = \left[\left(\frac{D_{c2}}{D_{c1}}\right)^3 * \frac{Q_1}{Q_2} * \frac{\Delta\rho_1}{\Delta\rho_2} * \frac{\mu_2}{\mu_1}\right]^{1/2} \quad (3)$$

On this step, d_2 was found for about 1.345 and used to transform the mean particle size from Table-2 on the pre-design column. Transformation of d_2 is shown in Table-3, column (3) to yield the scaled mean particle or the mean particle of the column (1) divided by d_2.

Table-3. Prediction of overall collected efficiency.

Pa. Size μm	Percentage in range	Mean Pa. Size, μm	ηi (%)	Collected,% (2)*(4)/100
(1)	(2)	(3)	(4)	(5)
>50	15.17	37.18	98.5	14.94
40-50	11.34	33.46	97.8	11.09
28-40	19.32	25.28	97.0	18.74
20-28	16.73	17.85	95.5	15.98
10-20	23.59	11.15	93.0	21.94
05-10	8.64	5.58	88.5	7.65
02-05	3.60	2.60	72.5	2.61
0-02	1.61	0.74	25.0	0.40
	100			93.3

The pressure drop of the cyclone separator designed is also important to be observed. It will give information of blower specification to be applied and the satisfactory operation. The pressure drop of the cyclone separator designed is calculated using equation (4):

$$\Delta P = \frac{\rho_g}{203}\left\{v_i^2\left[1 + 2\phi^2\left(\frac{2r_t}{r_e} - 1\right)\right] + 2v_o^2\right\} \quad (4)$$

Where ϕ is taken from the cyclone pressure drop factor [31] and the value of pressure drop for the pre-design prediction was about 332 Pa.

The particles that enter to the cyclone separator will be collected with 50% efficiency. The equation (5) and equation (6) developed by Lapple [12] is used to calculate the 50% cut diameter of the particle (d_{pc}) and the collection efficiency by equation (7), [20].

$$d_{pc} = \left[\frac{9\mu_2 b}{2\pi N_e v_i(\rho_p - \rho_g)}\right]^{1/2} \quad (5)$$

Where N_e is the number of airflow revolution:

$$N_e = \frac{1}{a}\left[h + \frac{H-h}{2}\right] \quad (6)$$

Finally, the collection efficiency of any size of particles given by:

$$\eta_i = \frac{1}{1+(d_{pc}/\bar{d}_{pi})^2} \quad (7)$$

Another analysis is for the PAH, benzo(a)pyrene compound (a PAH characteristic) contained in the smoked fish product was done by high-performance liquid chromatography (HPLC) method. HPLC is one method that very suitable for the determination of PAH in a variety of smoked meat products [28, 29]. In the experiment, this method used in triplo samples with a limit of detection (LOD) 0.25 μg/kg.

Experimental setup

The design of cyclone separator has dimensions as Table-4. The Dimensions of the cyclone separator are given as scales in Table-1 and the initial value of cyclone diameter is given in equation (1) - (2).

Table-4. Dimensions of cyclone separator.

Cyclone geometry	Dimension (m)
(1)	(2)
Diameter (D)	0.25
Height of inlet (a)	0,125
Width of inlet (b)	0,0625
Diameter of outlet (do)	0,125
Diameter of dust outlet (Bc)	0,09375
Length of cyclone body (h)	0,375
Length of cyclone cone (hc)	0.625
Total length (H)	1

An integrated cyclone separator with heat exchanger was developed at the mechanisation and agricultural equipment laboratory of Politeknik Gorontalo (Indonesia). The schematic diagram of that integration, as a unity of the smoke-heat generator, is shown in Figure-1.

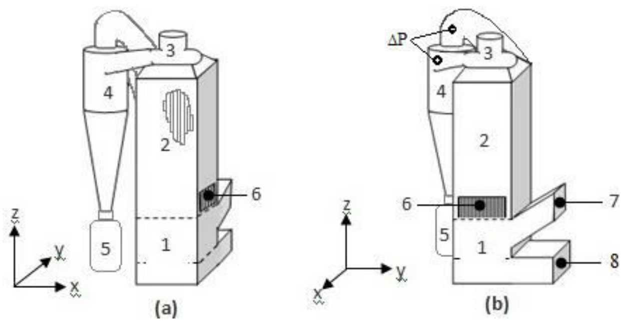

Figure-1. The smoke-heat generator, schema (a): (1) Furnace, (2) heat exchanger, (3) blower, (4) cyclone separator, (5) dustbin, (6) smoke outlet. Schema (b): (7) biomass feeder, (8) air/burning residue duct, and (ΔP) pressure drop of inlet/outlet cyclone with 5^{o} angle at inlet cyclone.

The performance of particles separation by the cyclone had already been tested and the particle size distributions are presented in Table-2, on the after-design column. These particles have a broader range of 0.2 - 600 μm. Calculation of the overall collection efficiency of particles separation uses equation (5) - (7) and it is shown in Table-5.

Table-5. Overall collected efficiency.

Pa. Size (μm)	Percentage in range	Mean Pa. Size, μm	ηi (%)	Collected,% (2)*(4)/100
(1)	(2)	(3)	(4)	(5)
>80	26.46	80.0	99.8	26.40
56-80	21.42	68.0	99.7	21.35
38-56	18.20	47.0	99.3	18.07
20-38	15.35	29.0	98.2	15.07
10-20	9.55	15.0	93.5	8.93
05-10	4.46	7.5	78.4	3.49
02-05	2.96	3.5	44.1	1.30
0-02	1.60	1.0	6.0	0.10
	100			94.7

The total pressure drop is calculated both the static pressure and the dynamic pressure for the cyclone inlet and outlet. The static pressure drop $(P_{is} - P_{os})$ of the cyclone inlet and outlet were measured by Hiyoshi model AP110. While the dynamic pressure drop $(P_{id} - P_{od})$ of the cyclone inlet and outlet were calculated by equations. The total pressure drop equation was adapted from Zhu *et al.* [40] as equation (8) below:

$$\Delta P = (P_{is} + P_{id}) - (P_{os} + P_{od}) \quad (8)$$

The dynamic pressure (P_d) of inlet and outlet were calculated under each condition according to the equation (9):

$$P_d = \rho_g \frac{V^2}{2} \quad (9)$$

The value of static pressure drop $(P_{is} - P_{os})$ and dynamic pressure drop $(P_{id} - P_{od})$ was 176 Pa and 28 Pa respectively.

RESULTS AND DISCUSSIONS

Cyclone efficiency

The collection efficiency and pressure drop of the cyclone separator are the major analyses to be done in this work. As a design process, there are sets of data and calculations used to result in a real dimension of the cyclone separator (pre-design). Cyclone separator designed in this work was based on the particle size distribution of ash brushed from the wall of a chimney, where the husk and coconut shell were burned down at the bottom. The smallest size of the particle as analysed by CILAS 1190 LIQUID was 0.2 μm with the amount of percentage (by weight less than 2 μm) was 1.61% (Table-2). While the largest size of the particle was 112 μm, thus the range size of the particle from the chimney was 0.2 – 112 μm. The pre-design of the cyclone separator was also

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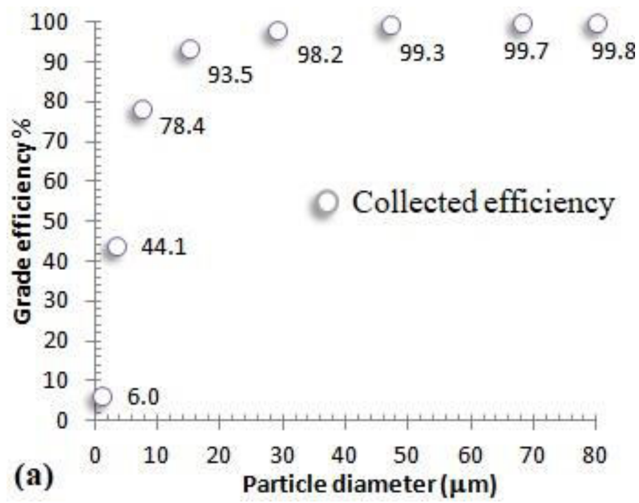
based on the calculations of high-efficiency Stairmand's cyclone including the set of data used from the standard design. In the pre-design, calculation of the overall collection efficiency as shown in Table-3 was 93.3%. This value satisfied the design of the cyclone according to the performance curves [30]. The design of the cyclone was also safe since the overall collection efficiency was more than 90%, which at least as the conventional type [6, 25, 38]. Meanwhile, the pressure drop of the cyclone separator as a prediction in the pre-design was about 332 Pa.

The particle size distribution of ash/dust analysed by CILAS instrument for separation performance of the cyclone designed had a more width range of 0.2 - 600 μm. In regards to similarity with the particle previously, both sources had the smallest particle size of 0.2 μm but slightly different in the amount of percentage (by weight less than 2 μm) equal to 1.6% (Table-2). The collection efficiency of the designed cyclone was 94.7 % (Table-5). This value has exceeded the prediction of 93.3 % although it was not too far, that it could be concluded to be valid. There are two types of cyclone separator related to the level of collection efficiency; more than 90% for conventional type and more than 90-95% for enhanced type. In the conventional type, the energy required is low with pressure drop in moderate to high (7.5-27.5 kPa) and categorised in very high flow capacity [38] adapted from Seville [25].

Commonly, description of the separation performance of the cyclone can be seen in Figure-2(a). In this graph, the grade of collection efficiency for particle diameter below 10 μm was only 78.4% of the highest, conversely, as much as 21.6% assumed to be passing through the cyclone separator.



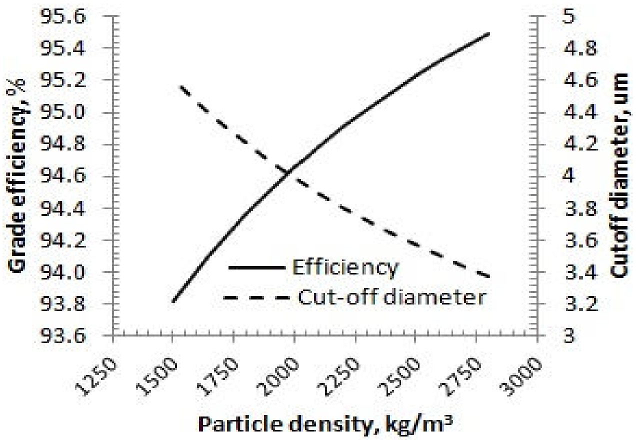


Figure-2. (a) Collection efficiency of any size particles, (b) Trendline of efficiency & cut-off diameter based particle density.

The particle of ash or dust that sized 0.2 μm was the smallest size, to be evidence either in the pre-design cyclone or in the after-design cyclone. As the number of these particles classified by weight less than 2 μm was 1.61% in pre-design and 1.6% in after-design, it could be stated that only 0.01% of particle that passes through the cyclone separator. In the same case were for particles classified by weight less than 5 μm and 10 μm whose difference of 0.65% and 4.83% respectively. On this view, the separation performance of particles size below 10 μm could reach over 90%, as seen as on the surface of the smoked fish product that very clean (visual observation). This fact was another perception of the separation performance according to the occurrence of the particle from the combustion of coconut shell. It is noted that the data on after-design was not a result of testing series with the data in pre-design.

The cut-off particle size diameter (d_{50}) was another performance indicator of a cyclone. It could be defined as a 50 percent of the particles size that was separated into the dustbin. Particles which were larger than d_{50} were more likely to be separated, on the contrary, particles which smaller than d_{50} was more liable to pass through the outlet of the cyclone. The cut-off particle diameter as Figure-2(a) for particle density of 2050 kg/m^3 with collection efficiency of 94.7 % was 3.94 μm, also shown in Figure-2(b). The collection efficiency was the main consideration in the choice of the cyclone separator for practical application. However, the collection efficiency of the cyclone varied with particle size, shape and density, the fluid throughput and the geometry of the cyclone [9]. In the Figure-2(b), it shows an increasing grade of collection efficiency for particle density in the range of 1500 - 2800 kg/m^3. It also illustrates the cut-off particle size which moved from about 4.6 to 3.4 μm for the same range of the particle density. Thus, these performances imply the different character of the cyclone separator for a different kind of biomass burning in the furnace. Solid-fluid density difference of the cyclone designed in this calculation was 2050 kg/m^3, which was

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taken from particle density of fly ash from coconut shell [16]. This value was chosen for at least two reasons. One is because of the same fuel of coconut shell that was burned in the furnace of the experiment. Another reason is the value which was lower than the fly ash particle of wood chip 2570 kg/m^3 with bulk density 660 kg/m^3 [11]. The bulk density of ash particle from the experiment of this cyclone separator was also lower, namely 521 kg/m^3.

Cyclone pressure drop

The pressure drop of the cyclone separator is an indicator for energy consumption level. The higher the pressure drop of a cyclone separator, the higher the energy consumed. The total pressure drop which was measured and calculated from equation (9) result in a value of about 204 Pa. The static pressure measurement of inlet and outlet of the gas stream was done nearly at ambient temperatures in which the ash particle possibility was loaded very slightly. The component of this static pressure and dynamic pressure of the cyclone was 176 Pa and 28 Pa respectively. This value was lower than the pressure drop that was predicted from equation (4) equal to 332 Pa. In the operational testing for fish smoking of 11.6 hours, the consumed energy was 1.28 kWh or equal to 4.6 MJ. The ratio of the consumed energy to the pressure drop of the cyclone separator was 22.6 MJ/Pa.

Solid particles

The particle size distributions by CILAS instrument that were done for fly ash particles from the chimney and those of collected in the dustbin were both similar in the smallest size. It was explained that the ash or dust particles, which were flying with smoke-air within cyclone, had the same characteristic as the fly ash particles brushed from the chimney. On the contrary, the differences between both sources of ash particles were in their ranges. The ash particles collected in the dustbin as a part of cyclone performance were wider than the ash brushed from the wall of the chimney. The ash particles from chimney were in the range only from 0.2 - 112 μm. It seems that the ash fraction was only influenced by the updraft forces of heat burning. On the one hand, the ash particles collected in the dustbin were influenced by centrifugal forces of the blower. Thus, the range was wider from 0.2 to 600 μm, which could be like other contaminants such as fine-fraction of charcoal and sand.

In comparison with the size of smoke particles, the range of ash or dust particles that separated by the cyclone was overlapped. Generally, particles of the smoke had sizes from 0.2 to 0.4 μm or as low as from 0.05 to 1 μm. So there was overlap in the range of 0.2 - 1 μm that affected the cleanliness of the smoke. The ash or dust particle with the average size of 1 μm as seen in Table-5 had a collecting efficiency by 6.0 %. The separation performance of this particle size also affects the smoke healthier from the fraction of tar. The residual of biomass burning could be in form of ash, char, and fraction either carbon black (soot) or tar that potentially harms the human health through smoked food. The carbon blacks were material considered as substances that potentially contaminated with carcinogenic aromatic hydrocarbons since certain of them had been shown to contain 3,4-benzpyrene [21, 37]. Carcinogenic hydrocarbon was also found in the food because of the smoking process. It was in much higher concentrations for smoked food that occasionally from contamination by soot [37].

Smoke, tar, and fine particles

Tars in some references are a complex mixture of organic compounds (including aromatic and heteroaromatic species as well as polycyclic aromatic hydrocarbon compounds PAHs) which condense at room temperature [14, 17]. Tar Formation according to empirical models, can be occurred either in low temperatures or in higher temperatures [36], in higher temperatures (300-500 °C) the molecule was rapidly depolymerized which further react to provide substance with tar component. At the temperature of 300 °C, the production level of tar had achieved 60% from cellulose under vacuum condition [26].

A specific discussion addressed to the fraction of tar mixed with smoke (fume/favour) and fine particles (smaller than the cut-off diameter), which were more likely to pass through the cyclone separator. On the smoke-heat generator design, there was a heat exchanger where the cyclone separator integrated between the bundle of tubes and shell structure with baffles. The travel of smoke with tar component in the bundle of tubes occurred with the effect of decreased temperature. The decreasing of temperature affects the tar to be condensate more easily. Furthermore, the centrifugal forces of blower caused more effects to the condensation process which, in fact, made the tar was spread and sticky to the surface inside the cyclone and also in the dustbin made of glass as seen in the Figure-3(a).

Figure-3. (a) Tar in the dustbin, (b) A cloth of masker blackening by the smoke-fine particle at the smoke outlet, (c) Appearance of the smoked fish.

The smoke with tar component and the fine fraction of ash particle smaller than d_{50} would pass through the cyclone via the outlet. The next barrier to them was the shell structure with baffles of the heat exchanger. On the shell structure that filled up with the criss-cross of tubes for one baffle, the smoke mixes tar and the fine fraction of ash particle would be turned around as much as five times. The baffles that applied as the smoke barrier to decrease PAH compound within tar was also accordingly with the recommendation of the Codex Alimentarius Commission [2]. Figure-3(b), a cloth of mask placed at the smoke outlet tried to catch the fine particle, but it was hard to analyse as only the black image found on it. While the Figure-3(c) shows a yellow-brown colour from the fish skin and clean as a smoked fish product. Thus, the fish which was processed with this new indirect smokehouse design could be diminished the PAH (benzo(a)pyrene) contamination under the Turkish Codex's maximum limit of 2.0 μg/kg, and also below the European Commission (EC) limit of 5.0 μg/kg [3, 33]. The level of benzo(a)pyrene analysed by HPLC method for fish smoked product in the experiment was 1.29 μg/kg.

CONCLUSIONS

The cyclone separator designed in this study had the overall collection efficiency by 94.7 %, which exceeded the prediction of 93.3 %. This efficiency level has satisfied the reference curve of performance and safe since the value exceeds 90%. The particle size distribution, either the ash particles from chimney or ash/dust particle separated by the cyclone, had the same smallest size of 0.2 μm, which was overlapping with the smoke particles size. The overlapping size of particles between ash and smoke indicated that separation of the ash/dust from smoke-air stream occurred from the smallest size to the larger with the increase of collection efficiency. In addition, the particles of ash or dust and tar fraction contained in the smoke were separated and sticky within cyclone, dustbin and the structure of heat exchanger. These performances were implicated to the smoke cleanliness and made it healthier for the fish smoking process. The content of benzo(a) pyrene as a characteristic of PAH compound in the smoked fish product was 1.29 μg/kg, which was the low level and safe to consume. Pressure drop as an indicator of energy consumption showed a lower value than that of the prediction and it had a ratio of energy consumption to the pressure drop of the cyclone about 22.6 MJ/Pa. This is to say that by the performance of efficiency, the smoke health that impact to low benzo(a) pyrene, and the pressure drop, it indicates that the designed cyclone is safe for practical purposes.

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Nomenclatures

a	Height of inlet, m
A_i	Cross section area of inlet, m^2
As	Surf. area of cyc. exposed to the spinning fluid,
b	m^2
Bc	Width of inlet, m
C1	Diameter of dust outlet, m
C2	Standard cyclone
d_2	Designed cyclone
d_{pc}	Scaling factor
d_{pi}	Cut particle dia. collected with 50%
D	efficiency, μm
do	Diameter of particle, μm
fc	Diameter of cyclone, m
h	Diameter of outlet, m
hc	friction factor, taken as 0.005 for gases
H	Length of cyclone body, m
N_e	Length of cyclone cone, m
ΔP	Total length of cyclone, m
P_s	Number of airflow revolution
P_d	Total pressure drop, Pa
Q_1	Static pressure drop, Pa
Q_2	Dynamic pressure drop, Pa
v	Standard volumetric flow rate, m^3/h
v_i	Designed volumetric flow rate, m^3/h
v_o	Velocity, m/s
ϕ	Inlet velocity, m/s
η	Outlet velocity, m/s
η_i	Cyclone pressure drop factor
μ_1	Efficiency of cyclone, %
μ_2	Efficiency of collection of any size particles, %
ρ_g	Test gas viscosity, $N.s/m^2$
ρ_p	Gas viscosity of designed cyclone, $N.s/m^2$
$\Delta\rho_1$	Gas density, kg/m^3
$\Delta\rho_2$	Particle density, kg/m^3
	Solid-fluid density diff. in stand. conditions, kg/m^3
	Solid-fluid density diff.of designed cyclone, kg/m^3

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