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Experimental Investigation on Filtration and Cooling Effect of Kitchen Hood Ventilation System from Water-Mist Recirculation Spray: Water-Mist Spray Cycle

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ABSTRACT

A Water-mist spray system in several heavy-duty kitchen hood canopies is installed to efficiently control the high heat loads and grease emissions produced from the cooking process and for safety purposes. The main purpose of this study is to reduce water consumption by introducing the water-mist recirculation system to replace the current method water-mist system since it is working as water loss. A standard ASTM 2519 and UL 1046 full-scaled experiment is developed in the laboratory. An existing Halton Europe/Asian water-mist operating system is adopted in this study. Twelve (12) cycles (at 24 hours of water-mist activation) have been studied to determine the maximum water-mist activation cycle. The data are collected at two (2) hours water-mist activation at every water-mist recirculation cycle. The water-mist spray fluids viscosity is 0.7 cP from fresh water until the 4th cycle (8 hours water-mist spray) and increase 14.29% (0.8 cP) at the 5th cycle to the 12th cycle. On average, the difference in gas emissions percentage for CO concentration between fresh water until the 4th cycle is 10.81 – 18.92% while the CO_2 concentration is 12.33 – 18.22%. On average, the difference in cooling effects percentage for ducting temperature between fresh water until the 4th cycle is 5.55% while the hood temperature is 2.33%. From the study, the water-mist recirculation system could save up to 611,667 litres per year and 466,798.5 litres per year water for all U.S, European, and Asian kitchen hood designs per hood length. By adopting the new water-mist recirculation system to the current water-mist kitchen hood, the water operational cost for water successfully reduced to RM 4,889.63 per year and RM 6,977.86 per year for U.S design and European or Asian design per hood length respectively. The water-mist recirculation system has great potential to improve the current water-mist system for the commercial kitchen hood.

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1. Introduction

The majority of cooking operations especially in a commercial kitchen generate emission and particulate matter that significantly contributed to air pollutants and affected human health. Cooking-particulates were emitted from small scale food outlets in the form of smoke and fumes from barbecuing, roasting, and wood-fired cooking [1].

Some wood-fired pizza ovens use gas for cooking with a small wood fire to add flavour. The gas fire reduces odours but not particles in the wood smoke. The particles consist of partially burnt fats emitted from the cooking meat and woodsmoke. These were known to contain materials detrimental to health such as polyaromatic hydrocarbons (PAHs) and fine particulate matter (PM2.5) [2-3]. Fine particulate matter (PM2.5) refers to tiny particles or droplets contains in the air that is two and one-half microns or less in width and cause the air to appear hazy and reduce visibility when levels were elevated.

Grease particles and aerosols can also be generated from certain cooking processes. From the ASHRAE 1375 final report [4], the results of the emission tested indicates that the wok had the largest total grease emission in the plume, 112.037 kg grease/453.592 kg food cooked, nearly a factor of two over the appliance with the second-highest emission, the solid fuel broiler at 64.410 kg grease/453.592 kg food cooked. The conveyor broiler had 227.703 kg grease/453.592 kg food cooked whereas the other appliances were less than 14. The total grease emissions in the exhaust duct were less than the values in the plume primarily because the plume mass emissions were often dominated by particles larger than 10 µm in size. These large particles rarely made it into the exhaust duct to be sampled by the instrumentation located there. Thus, the total grease mass emissions in the exhaust duct ranged from 32.885 kg grease/453.592 kg food product for the solid fuel broiler to 1.1974 kg grease /453.592 kg food product for the conveyor pizza oven [4]

Nowadays, many kitchen hoods are equipped with mechanical grease filters such as cyclonic KSA and baffles plate to filter the grease emission from the cooking process. During the cooking operation, the mechanical grease filter or extractor is only efficient to capture particulate sizes larger than 10µm [2, 4, 5]. In a real situation, the particulate size ranged from 0.5µm and up to 20µm depends on the cooking styles [4].

To increase the emission filtration efficiency, the kitchen hood was equipped with a combination of the mechanical grease filter and cold-mist spray. It had revealed that the cold-mist sprays can capture the grease particulate size range from PM2.5 to PM10 by increasing the diameter of grease particles from the temperature drop and grease vapor solidified during the cold-mist process [6]. Until now, there was no publication and report documented to reveal and prove the result even though it was possible in theory. Thus, it has been challenging research to determine the efficiency of the small grease particulate that is filtered by the cold-mist recirculation spray since it deals with the combinations of treated water, cooking emission and particulate matter.

The particulate portion of cooking emission varies in particle size as reported in ASHRAE RP 745 [7]. The mechanical grease extractor was one of the solutions to filter the grease from the cooking operations. Theoretically, the maximum efficiency of the grease extractor ranges from 2% to 70% depending on the cooking operations [7]. The mechanical grease extractor was only capable to effectively capture large particulates but not extract vapour as it was poor in capturing small particles. Previous research reported that the efficiency of the mechanical grease extractor was close to 100% for particle sizes larger than 10µm [5].

The efficiency of the grease filtration inside the plenum can be increased by adopting the cold-mist spray. The water-mist cooling was an effective technique to remove heat and the heat transfer rate could be increased significantly [8]. The water-mist spray was normally installed at the location before entering and after exiting the mechanical grease extractor. The cooking particulate and vapour pass through the cold-mist spray that causes the grease particles to drop in temperature, solidify, and increase in particle sizes.

Unfortunately, the water-mist process increases the water consumption, which was a part of the operational costs to the user and increases the impact to the environment from the water pollutant. The wastewater from commercial water-mist kitchen hood ventilation system has a significant impact on environmental issues and increases the water consumption in water spraying for cooling and smokes concentration [9], and to filters the high gas emissions especially CO and CO_2 produced from heavy-duty kitchen appliances. The previous study conducted by Halton R&D Center France [10] claimed that the water consumption for the cold-mist process was currently high at 533.484 m^3 per year for a 5-meter length US designed water-mist kitchen hood. Thus, the water-mist recirculation system is the solution to the current emission filtration process in heavy-duty cooking operations to minimise the operational costs as well as the impact on the environment.

1.1 Effects of Fluids Viscosity on Spray Characteristics

Absolute (dynamic) viscosity in spray was a liquid property which was a quantity measure for force needed to resist internal friction in a liquid during flow. Absolute viscosity was a main factor for spray pattern formation, spray angle, and droplets size. The high value of viscosity increases the SMD [11]. Liquid viscosity has an important effect on the spray angle and breaks up especially in swirl atomizers. High viscosities of liquid will produce a large spray angle and is difficult to break up compared to less viscosities [12]. The fluid viscosity affects the spray characteristics such as spray pattern, spray angle, spray pressure, spray velocity and droplet size. As the fluids viscosity increase, the spray pattern changes, the spray angle decreases, the spray flow rate decreases, and the spray droplet velocity decreases [13].

1.2 Commercial Kitchen Hood System

The developments of the kitchen hood technologies have grown especially in the hotel and restaurant sector. Each kitchen hood presents a new design; functionality and technology include the effectiveness of the ventilation system. Traditional commercial kitchens become hot because of a complicated component in the ventilation system including the makeup air system, hood exhaust and air supply. An uncomfortable kitchen will contribute to low productivity, efficiency, and affect staff comfort [14]. The reason to install a kitchen hood system is to remove smoke and heat, and reduce thermal plume and other contaminants during the cooking process. Furthermore, the airflow condition is to reduce the thermal plume and comfort for the kitchen staff. The productivity can drop by 30% if the temperature in the kitchen area increases by 5.5°C (10°F). The equipment from a new commercial kitchen will release heat in the form radiation and convection. The hood system will capture the hot cooking surface from the convection and radiation process [14-16]. A proper ventilation system was necessary and give impacts of the temperature on airborne particles [17]. The thermal effectiveness of the air was decreases with increasing air flow velocity in the air ducts [18].

1.3 Water Consumption for Current Water-mist Kitchen Hood Process.

To estimate the current operating cost, two typical locations is selected which are France for Europe and Lawrence KS for US. These two selected locations were interesting because they are close to the average water and sewer cost of their continent. The operating time per day of 14 hours, 7 days per week is selected in this case, which was the same as in the Cold Mist On Demand (CMOD) study by Halton R&D. Operating cost gives direct impact to the users. There are many factors to be considered estimating the water-mist operating consumption and cost. Table 1 shows the water consumption and operating cost for the Halton water-mist system. The previous study was conducted by Halton R&D Center France [10] the water consumption for cold-mist process was currently high at 4414 m^3 per year for 3 meter hood length and 7435 m^3 per year for 5 meter hood length US design water-mist kitchen hood. For European and Asian Design, the water-mist water consumption for cold-mist process high at 1403 m^3 per year for 3 meter hood length and 2364 m^3 per year for 5 meter hood length.

Table 1
Water consumption and operating cost for Halton kitchen hood water-mist process [9]

	U.S Design		European / Asian Design	
	Lawrence KS 1	Lawrence KS 2	France 1	France 2
Cold water price (Euro/m^3)	1.60	1.60	3.01	3.01
Hood length (mm)	3000	5000	3000	5000
No of nozzle (Water-mist)	38	64	16	27
Operating pressure (Bar)	2.76	2.76	1.67	1.67
Waterflow / nozzle (L/min)	0.38	0.38	0.29	0.29
Total waterflow (L/min)	14.44	24.32	4.6	7.7
Operating time, (hour/day)	14	14	14	14
Operating day per week	7	7	7	7
Cold water (L/day)	12127	20425	3855	6505
Cold water (L/week)	84891	142974	26983	45534
Cold water (m^3/year)	4414	7435	1403	2364
Cold water cost (Euro/year)	7,064.00	11,897.00	4,223.00	7,127.00
Cold water cost (Myr/year)	35,293.16	59,439.79	21,098.95	35,607.92

2. Methodology

The test equipment set-up as shown in Figure 1 based on ASTM 2519 [18] and UL 1046 standards [20], [22-24]. The water mist kitchen hood installed complete with a square 16-inch ventilation system and air filtration system. The air filtration system consists of two air filters, which are the panel filter (G4) and bag filter (F8). The maximum final resistance for both filters measurements and air filters performance ratings were based on the U.S. minimum efficiency reporting value MERV ratings (ANSI/ASHRAE 52.2) and Australian Standard ratings AS1324.1 [21]. The air resistance measured by using two digital manometers. The static pressure measured in the Pa unit is used to determine and monitor the resistance of an air filter for both G4 and F8 air filters. The air filters changed once they reached the maximum resistance and weighted before and after the experiment to determine the weight of penetrated FOG collected by the air filters.

As shown in Figure 1, the grease generator used is placed at the bottom of the kitchen hood. The grease generator which produced smoke that contains FOG was consistently generated Figure 2. Two stoves are used to generate the heat to produce vapours from the activation of the dripping flow mixtures of vegetable oils and water into a loading pan. The loading pan is preheated to 385±14°C and the temperature is controlled by adjusting the inlet LPG valve manually. The loading pan temperature obtained from the Pico data logger where two K-type thermocouples are installed inside the vapour box. The flow rates of vegetable oil and water is set by using two dosing pumps (SEKO Tekna Evo model 500). The dripping flow into the loading pan is set at the rate of 10±0.5 and 24.5±0.5 ml/minutes for oil and water respectively.

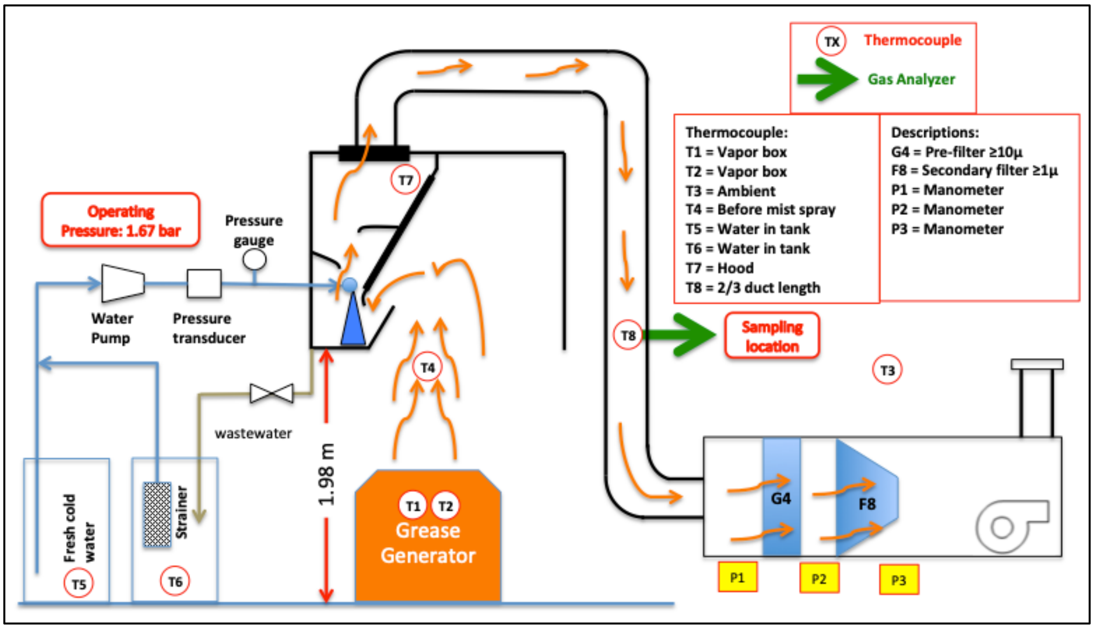


Fig. 1. Schematic diagrams of the water-mist recirculation system

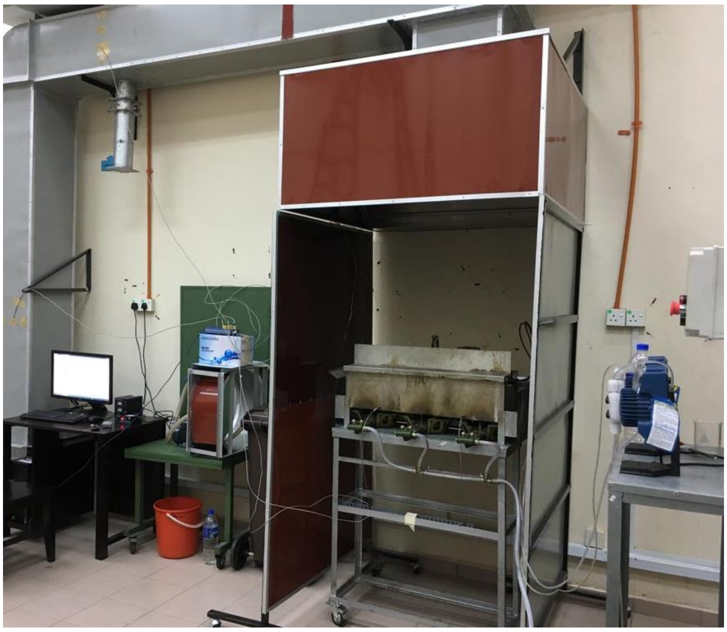


Fig. 2. Grease generator (UL 1046) test rig

2.1 Water-mist Recirculation System

A full-scale test of the kitchen hood with water mist exhaust plenum is carried out and the dimension of the hood and ducting system is similar to the UL 1046 and ASTM F2519-05. The water-mist kitchen hood exhaust plenum installed on the experimental test rig is manufactured by Halton Foodservice (M) Sdn. Bhd. The type of water mist spray nozzles used in this test is 1/8 KJSB 0.5 and manufactured by John Brooks Company which is similarly installed by Halton Food Services. There are six (6) nozzles installed horizontally along 1219 mm kitchen hood length with the integration of 170 mm distance between nozzles as shown in Figure 3.

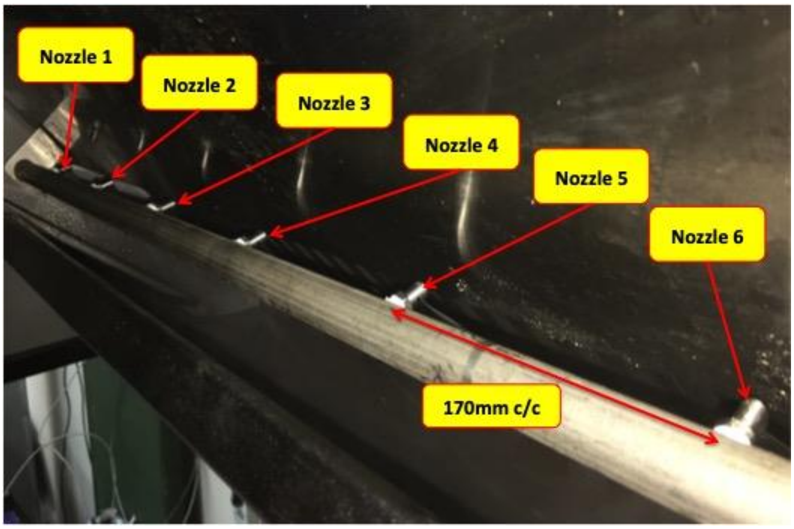


Fig. 3. Water-mist spray (mist curtain) operated

2.2 Experimental Parameter

To study the grease filtration efficiency by the water-mist recirculation system, the experimental parameter is based on Halton U.S and Halton Europe canopy operating conditions. The installation of the kitchen hood ventilation system is based on ASTM 2519-05 and UL1046. The grease machine is selected as a cooking load in this study for consistency and the standard operating condition complied with the UL 1046 standard. Table 2 shows the experimental parameter selected to perform this study.

Table 2
Experimental parameter

Type of canopy	Halton water-mist KSA single canopy
Nozzle types	1/8 KSJB 0.5 (Flat fan spray)
Integration	1 row of nozzle every 170 mm
Operating pressure	1.67 bar
Flow rate / nozzle at operating pressure	0.29 l/min
Air flow rate	5663 to 8495 L/min (200 to 300 cfm) per linear foot of mechanical grease filter length (UL 1046)
Water-mist condition	Fresh water, recycled water
Operating per cycle	2 hours / 120 minutes – grease loading (UL 1046)

The inlet pressure of the working fluid is set to 1.67 bar at a water-mist spray flow rate of 0.29 l/min per nozzle. The pressure transducer is installed to set the water-mist flow rate. The accuracy of the flow rate from the pressure transducer reading is calibrated traditionally from the fraction of the fluid volume and time taken. The K-type thermocouples and gas analyzer (Optima 7) is installed as in Figure 1 for temperature measurements and gas sampling at sampling location inside ducting. Continuous measurement of temperature, CO, and CO_2, is recorded at 22 minutes of idling time, 120 minutes of grease loading and water-mist activation, and 10 minutes before shutting down the KHV system. Figure 4 shows the test configuration for the water-mist recirculation system.

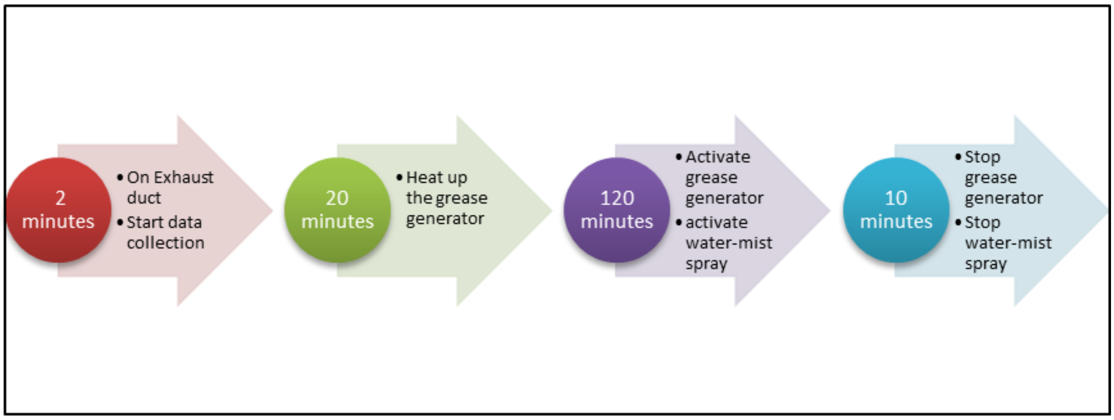


Fig. 4. Test configuration for the water-mist recirculation system

Two types of filters are installed in the air filtration unit to measure the mass concentration of the particles and vapour passing through the exhaust ducts. The pre-filter, secondary filter, vegetable oil (grease machine), and water (grease machine) are weighed at the start and the end of the test. Air is supplied to the test room and the exhaust airflow is set at actual pressure 70 ± 5 Pa at an actual airflow rate range from 800 to 1200 cfm.

Table 3 shows the test conditions for experimental analysis for the water-mist recirculation system. At no-mist test condition, the operating system is without water-mist spray activation for 2 hours grease load. For fresh water, cycle 1 to cycle 12 test conditions, the water-mist spray is activated for 2 hours grease load for each test condition. The 2 mechanical grease filters for 1.2 meters hood length which are installed inside the kitchen hood plenum in this test is made completely of a material stainless steel. It is complying with UL1046 grease loading test method, where the minimum of 2 hours grease load samples shall be carried out for filters that are made completely of a material having non-absorbing surface.

Table 3
Test conditions for experimental analysis

Test Conditions	Water-mist spray cycle, (hours)	Operating System
No-mist	-	Without water-mist spray activation
Fresh water	0	Fresh water (Current operating system)
Cycle 1	2	Recirculation system
Cycle 2	4	Recirculation system
Cycle 3	6	Recirculation system
Cycle 4	8	Recirculation system
Cycle 5	10	Recirculation system
Cycle 6	12	Recirculation system
Cycle 7	14	Recirculation system
Cycle 8	16	Recirculation system
Cycle 9	18	Recirculation system
Cycle 10	20	Recirculation system
Cycle 11	22	Recirculation system
Cycle 12	24	Recirculation system

2.3 Wastewater Properties Measurement

A water-mist wastewater sample is collected inside the strainer (where it is installed in the water tank) to determine the fluid properties. These samples are then delivered to the laboratory to measure the mass and viscosity of the fluids. A viscometer is used to measure the viscosity of the wastewater. The mass of the wastewater measured using an analytical balance. The Density (ρ) of each wastewater sample is determined from the analytical balance test.

In this test, the viscometer is used to measure the wastewater viscosity. The viscometer used in this test was able to read the viscosity of the fluid at one decimal point. The analytical balance used in this test has an accuracy to read in 1 milligram. From the fluid mass data, the density of the fluids is obtained from the fraction of the fluid mass and fluid volume (100 *ml*).

The wastewater samples are tested in FKMP, UTHM Laboratory. Each sample was filtered before measuring the mass using an analytical balance. Next, the wastewater volume is measured using a laboratory volume cylinder. The volumetric of each sample is standardized to 100ml. After that, each wastewater sample is measured using the analytical balance test and the mass of each sample is recorded. Finally, the same wastewater sample tested from the analytical balance test is used to determine the viscosity of each sample using a viscometer.

3. Results

3.1 Exhaust T.A.B

The test airflow rate is validated from testing and balancing (T.A.B) the hood measurements. The exhaust T.A.B readings measured in this study are compared with the manufacturer exhaust T.A.B versus airflow data. There are three data collected during this test. The first exhaust T.A.B data is collected without air filters installed to the system at an airflow rate of 57,500 L/min (2030.6 *cfm*). The second exhaust T.A.B data is measured with two (2) air filters installed to the system with G4 and F8 air filter initial resistance at 30 Pa at airflow rate 33,810 L/min (1194 *cfm*), Finally, the third exhaust T.A.B data is measured at the maximum resistance reach by both G4 at maximum resistance 250 Pa and F8 at maximum resistance 450 Pa air filter at airflow rate 24,069 L/min (850 *cfm*).

As in Table 4 and Figure 5, the exhaust T.A.B at airflow 24,069 L/min (850 *cfm*) recorded at 12 Pa was 4.35 percent than the exhaust T.A.B reading from the hood manufacturer data (Halton). At airflow 57,500 L/min (2030.6 *cfm*), the exhaust T.A.B reading was 67 *Pa* was 3.07 percent than Halton exhaust T.A.B reading. The exhaust T.A.B at airflow 33,810 L/min (1194 *cfm*) recorded 24 Pa was 4.35 percent than Halton exhaust T.A.B reading. As a result, the T.A.B readings at airflow 24,069 L/min (850 *cfm*), 33,810 L/min (1194 *cfm*), and 57,500 L/min (2030.6 *cfm*) were accepted since the percentage of error between the manufacturer specifications is less than 5 percent at each test. The accuracy of the instrument used to measure the static pressure TSI VelociCalc Plus 8386 is ±1% of reading ±0.005 in H2O (±1 Pa or ±0.01 mmHg) ± 0.03%/°C (0.02%/°F).

Table 4
Experiment Exhaust T.A.B Measurement Results

Airflow, L/min	HALTON T.A.B, *Pa*	Experiment T.A.B, *Pa*	Error, %
24,069 (850.0 *cfm*)	11.5	12	4.35
33,810 (1194.0 *cfm*)	23.0	24	4.35
57,500 (2030.6 *cfm*)	65.0	67	3.07

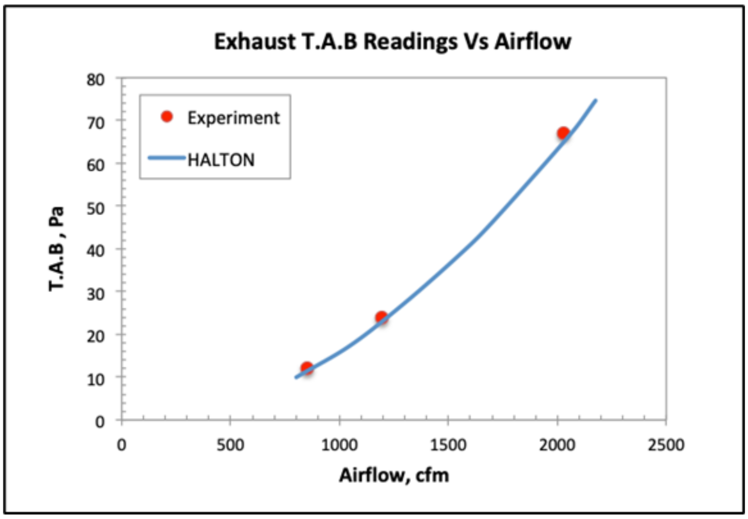


Fig. 5. Experiment exhaust T.A.B readings for 3 airflow

3.2 Temperature of Water-mist Recirculation System

The average hood temperature at grease loading (Process III) without water-mist activation recorded the highest result which was 51.4°C. From Figure 6, the average hood temperature during grease loading time (Process III) dropped 20.56% during water-mist activation for fresh water. The average hood temperature for water-mist activation for fresh water was 40.9°C. The average temperature dropped by utilizing the water-mist spray was 10.5°C.

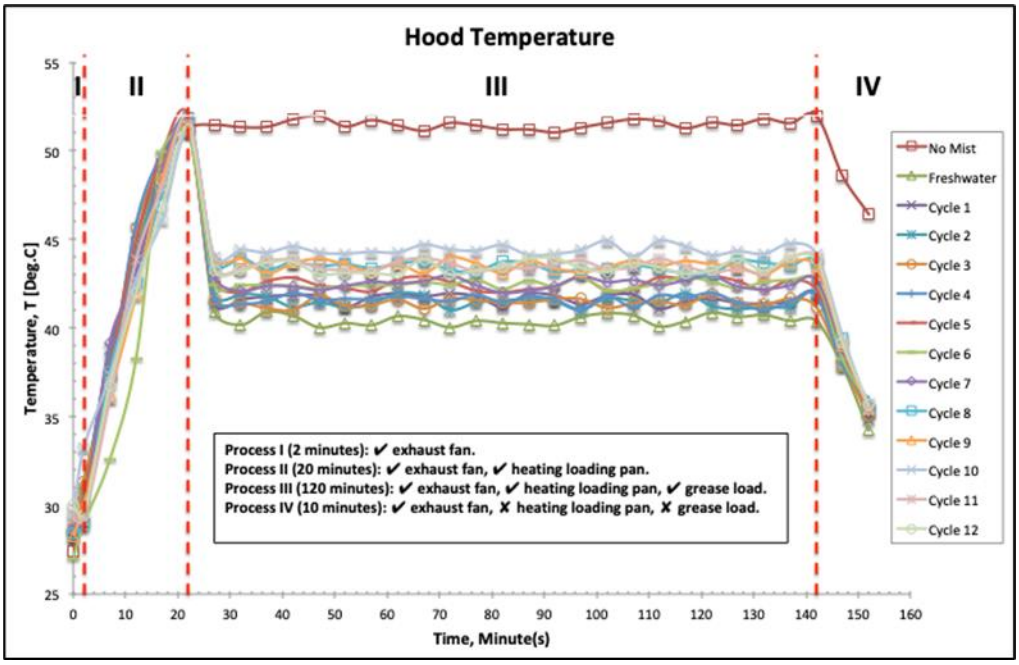


Fig. 6. The average hood temperature at all cycles

The average ducting temperature at grease loading (Process III) for without water-mist activation recorded the highest result which was 40.9°C. From Figure 7, the average ducting temperature during grease loading time (Process III) dropped 11.11% (4.5°C) during water-mist activation for fresh water. An average ducting temperature data recorded for water-mist activation for fresh water was 36.4°C.

The average temperature drops inside the ducting at location B2 by utilizing the water-mist spray was 4.5°C.

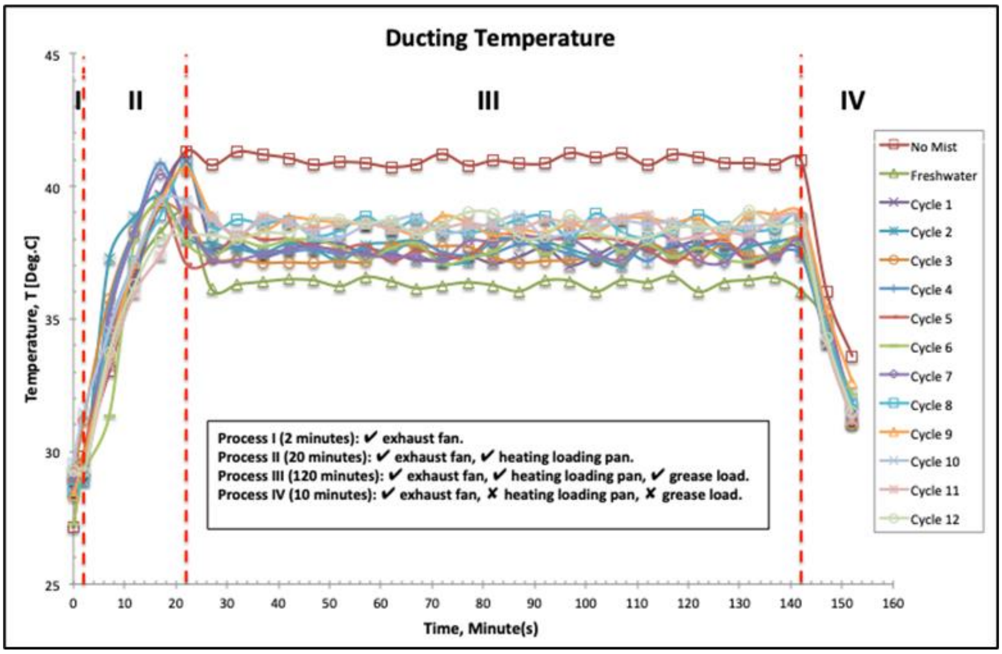


Fig. 7. The average ducting temperature at all cycle

3.3 Concentration of Carbon Dioxide, CO_2

The average concentration of CO_2 at grease loading (Process III) for without water-mist activation recorded the highest result which was 853 ppm. From Figure 8, the average concentration of CO_2 during grease loading time (Process III) dropped 38.27% (326 ppm) during water-mist activation for fresh water. An average concentration of CO_2 data recorded for water-mist activation for fresh water was 526 ppm. The average concentration of CO_2 decreased 326 ppm inside ducting at the location by utilizing the water-mist spray.

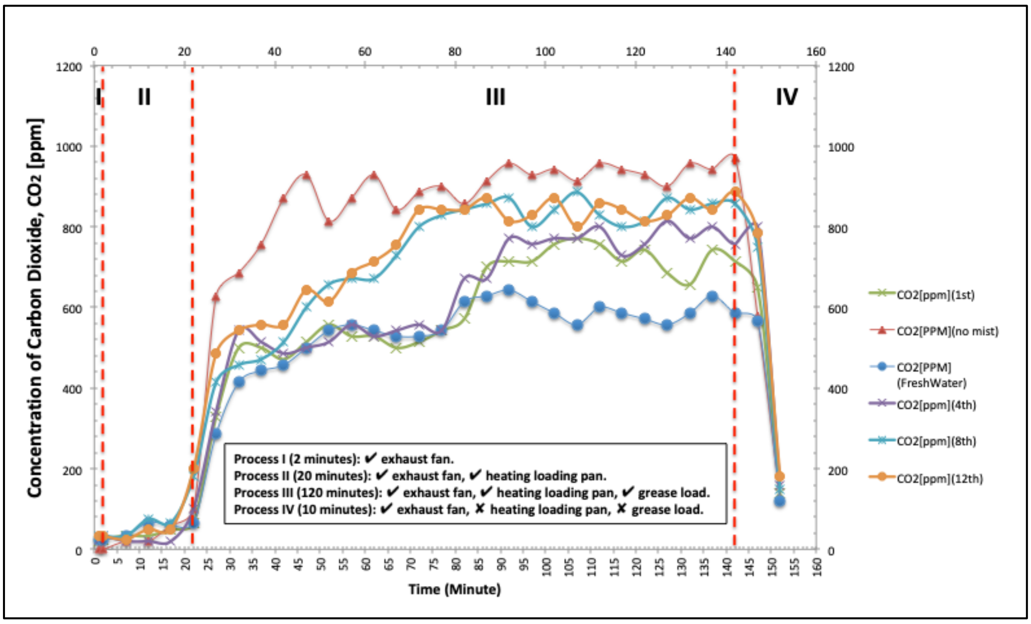


Fig. 8. The concentration of CO_2 for No mist, Fresh water, Cycle 1, 4, 8 and 12

The average concentration of CO_2 results during grease loading time (Process III) for Cycle 1, Cycle 4, Cycle 8, and Cycle 12 are 591 ppm, 622 ppm, 718 ppm, and 736 ppm respectively. Cycle 1 and Cycle 4 show similar average concentrations of CO_2 results during grease loading time (Process III) where the average concentration of CO_2 ranged between 591 ppm to 622 ppm. The average concentration of CO_2 increased 12.37% (65 ppm) to 18.26% (96 ppm) between Cycle 1 to 4 compared to fresh water. During this 8-hour (up to Cycle 4) grease loading, the water-mist sprays from the recirculation system showed great effects as the fresh water for the gas emissions filtration purpose.

Based on Figure 8, the average concentration of CO_2 data during grease loading time (Process III) for Cycle 8 and Cycle 12 are 718 ppm and 736 ppm. The average concentration of CO_2 increased 36.45% (191 ppm) at Cycle 8 and increased 39.86% (209 ppm) at Cycle 12 compared to fresh water. During this 24-hour water-mist recirculation system spray activation, the average concentration of CO_2 increased almost 200 ppm compared to fresh water. This shows that the average concentration of CO_2 dropped 116 ppm (13.66 %) compared to no mist (without water-mist spray activation) at 24 hours water-mist spray from the recirculation of the water-mist spray.

3.4 Concentration of Carbon Monoxide, CO

The concentration of carbon dioxide, CO is measured using the Optima 5 gas analyzer where the gas-sampling probe is placed at the sampling location. Figure 9 shows the concentration of CO data for without water-mist activation, water-mist activation from fresh water and water-mist activation from the recirculation system for cycles 1, 4, 8, and 12.

The average concentration of CO at grease loading (Process III) for without water-mist activation recorded the highest result which is 59 ppm. From Figure 11, the average concentration of CO during grease loading time (Process III) dropped 38.23% (22 ppm) during water-mist activation for fresh water. The average concentration of CO data recorded for water-mist activation for fresh water is 36 ppm. The average concentration of CO decreased 22 ppm inside the ducting at the location by utilizing the water-mist spray.

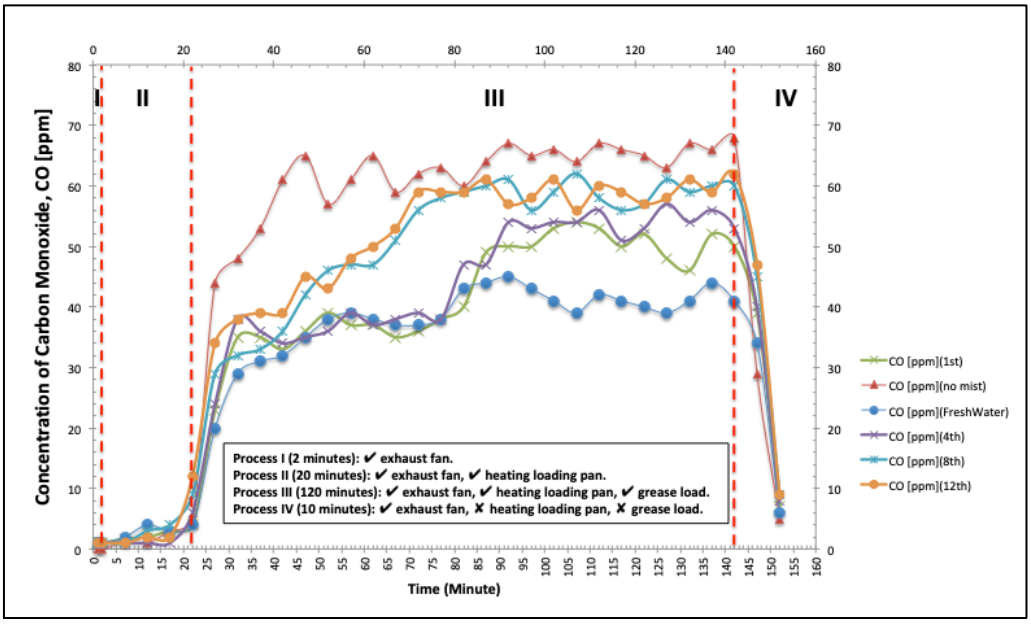


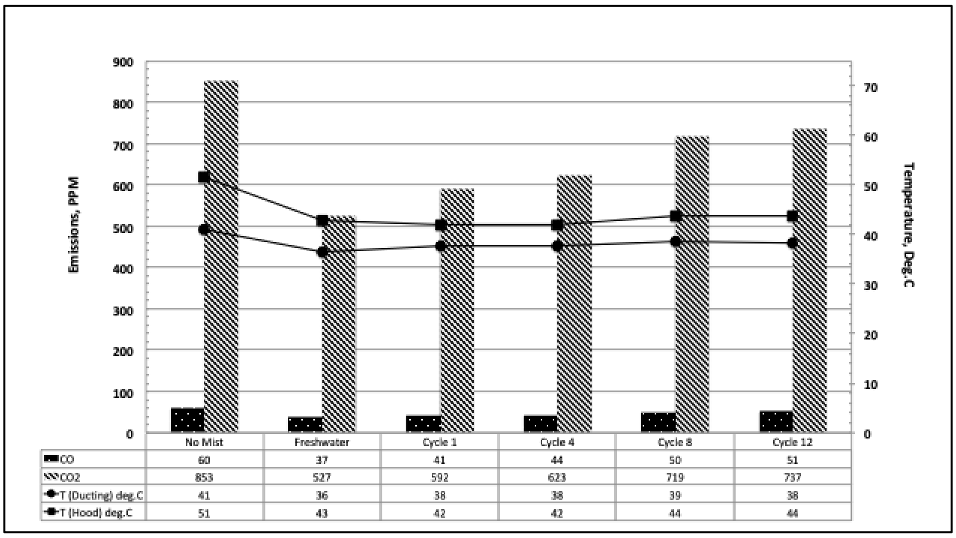
Fig. 9. The concentration of CO for No mist, Fresh water, Cycle 1, 4, 8 and 12

The average concentration of CO results during grease loading time (Process III) for Cycle 1, Cycle 4, Cycle 8, and Cycle 12 are 41 ppm, 43 ppm, 50 ppm, and 51 ppm respectively. Cycle 1 and Cycle 4 show the similar average concentration of CO results during grease loading time (Process III) where the average concentration of CO ranged between 41 ppm to 43 ppm. The average concentration of CO increased from 12.38% (4 ppm) to 18.24% (6 ppm) between Cycle 1 to 4 compared to fresh water. During this 8-hour (up to Cycle 4) grease loading, the water-mist sprays from the recirculation system showed great effects as fresh water for the gas emissions filtration purpose.

From Figure 9, the average concentration of CO data during grease loading time (Process III) for Cycle 8 and Cycle 12 were 50 ppm and 51 ppm. The average concentration of CO increased 36.16% (13 ppm) at Cycle 8 and increased 39.74% (14 ppm) at Cycle 12 compared to fresh water. During this 24-hour water-mist recirculation system spray activation, the average concentration of CO increased almost 15 ppm compared to fresh water. It shows that the average concentration of CO dropped to 8 ppm (13.68%) compared to no mist (without water-mist spray activation) at 24 hours water-mist spray from the recirculation of the water-mist spray.

3.5 Average Temperature and Emissions at 2 Hours Grease Loading Time

The average temperature and gas emissions at two (2) hours grease loading time for data without water-mist activation, fresh water-mist spray, and recirculation water-mist spray is presented in Figure 10.

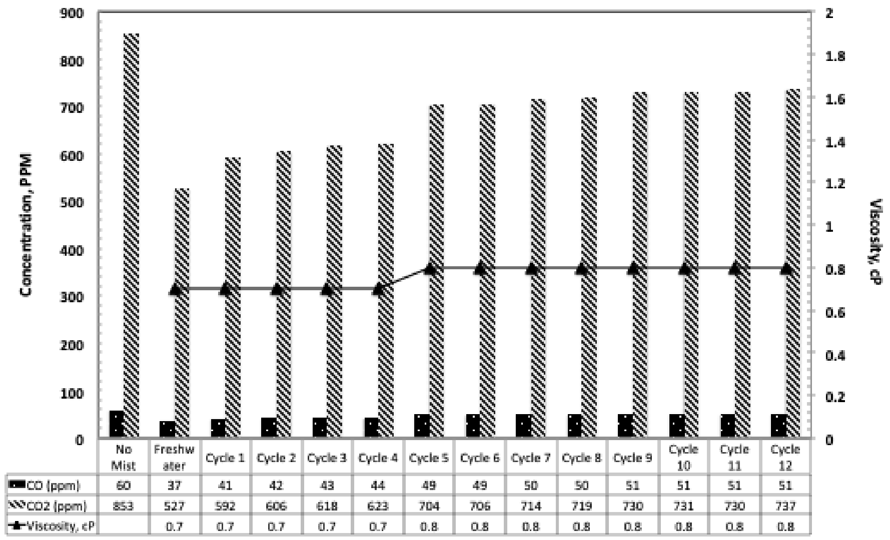


	No Mist	Freshwater	Cycle 1	Cycle 4	Cycle 8	Cycle 12
■ CO	60	37	41	44	50	51
▨ CO2	853	527	592	623	719	737
● T (Ducting) deg.C	41	36	38	38	39	38
■ T (Hood) deg.C	51	43	42	42	44	44

Fig. 10. The average gas emissions (CO and CO_2) and temperature (ducting and hood at loading time

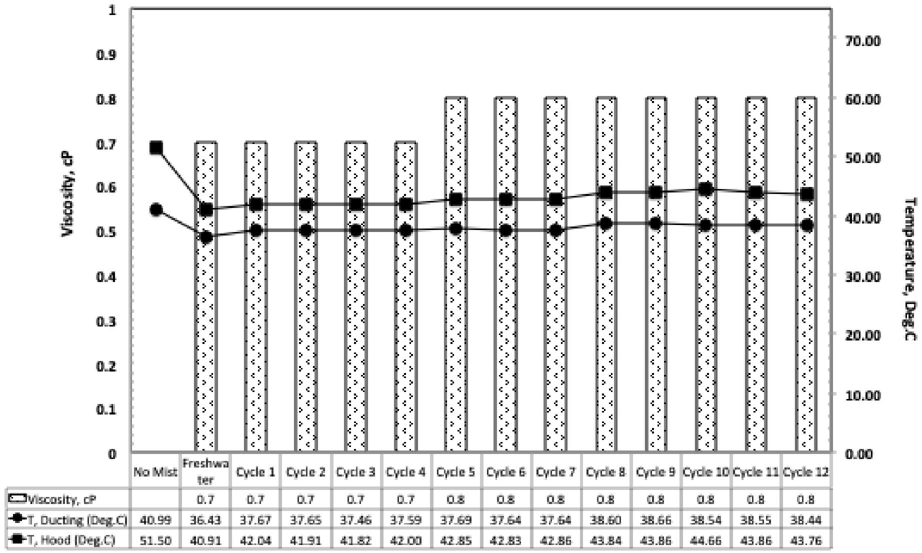
The difference in gas emissions percentage for CO concentration between fresh water until the 4th cycle is 10.81 – 18.92% while the CO_2 concentration is 12.33 – 18.22%. On average, the difference in cooling effects percentage for ducting temperature between fresh water until the 4th cycle is 5.55% while the hood temperature is 2.33%. The ambient temperature is controlled at 28°C ± 1.0°C and relative humidity (RH) at 79.5 ± 5. The water temperature inside the recirculation tank for fresh water-mist is 29.0°C. Meanwhile the water temperature inside the recirculation tank for cycle 1, 4, 8, and 12 are 29.3°C, 30.8°C, 30.8°C, and 30.9°C.

The best performance of the water-mist recirculation system in this study was up to the 4th cycle (after 8 hours grease loading time). The freshwater and wastewater from the water-mist spray have slightly different liquid properties such as density and viscosity. Based on Figure 11 and Figure 12, at the same fluid viscosity 0.7 cP, the average temperature of the hood and ducting at loading time are similar. At average concentration of CO_2, the fluids viscosity at 0.7 cP remained until the 4th cycle (at 8 hours spray). The concentrations of CO_2 slightly increased at almost to 100 ppm until the 4th cycle. However, at fluids viscosity 0.8 cP, the concentrations of CO_2 increased to 704 ppm.



	No Mist	Freshwater	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12
■ CO (ppm)	60	37	41	42	43	44	49	49	50	50	51	51	51	51
▨ CO2 (ppm)	853	527	592	606	618	623	704	706	714	719	730	731	730	737
▲ Viscosity, cP		0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Fig. 11. The average concentration of CO & CO_2 and fluids viscosity at loading time



	No Mist	Freshwater	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12
☐ Viscosity, cP		0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
● T, Ducting (Deg.C)	40.99	36.43	37.67	37.65	37.46	37.59	37.69	37.64	37.64	38.60	38.66	38.54	38.55	38.44
■ T, Hood (Deg.C)	51.50	40.91	42.04	41.91	41.82	42.00	42.85	42.83	42.86	43.84	43.86	44.66	43.86	43.76

Fig. 12. Average temperature (ducting and hood) and fluids viscosity at loading time

3.6 Water-mist Recirculation System Cost Analysis

This clearly shows us that under these conditions, the water-mist hood represent an operating cost for the user. The recirculation water-mist system will reduce the water cost at RM 4,889.63 per year and RM 6,977.86 per year for U.S design and European or Asian design respectively as shown in Table 5.

One of the objectives of this study is to reduce the water consumption for the current water-mist kitchen hood ventilation system. By adopting the water-mist recirculation system to the current water-mist kitchen hood ventilation system, the water can be reduced to 1,675.80 L/day and 1,278.90 L/day for U.S design and European or Asian design. In a year, 611,667 L and 466,798.5 L water can be reduced and gives direct impact to users as well as to our environment by minimising water pollutant.

Table 5
Water-mist operating cost comparison

	US Design		European / Asian Design	
	Current	Recirculation (8 hours)	Current	Recirculation (8 hours)
Tariff (Euro/m^3)	1.60	1.60	3.01	3.01
Number of nozzle (water-mist)	6	6	6	6
Operating pressure (bar)	2.76	2.76	1.67	1.67
Water flow per nozzle (l/min)	0.38	0.38	0.29	0.29
Water flow at nozzle (l/min)	2.28	2.28	1.74	1.74
Operating time hours/day	14	14	14	14
Fresh water (l/day)	1,915.20	239.40	1,461.60	182.70
Fresh water (l/year)	699,048	87,381	533,484	66,685.50
Fresh water (m^3/year)	699.048	87.381	533.484	66.690
Total water cost (Euro/year)	1,118.48	139.81	1,605.79	200.72
Total water cost (Euro/month)	93.21	11.65	133.82	16.73
Saving /year (Euro/year)		978.67		1,405.07
Saving /year (Myr/year)		4,889.63		6,977.86

4. Conclusions

A full-scale KHV system and grease machine (for cooking load) have been developed at Halton-CEIES Laboratory (size, material, and procedure are referred from ASTM 2519-05 and UL 1046). The water-mist recirculation system is tested experimentally by comparing the temperature drop, emission filtration efficiency, and water properties with the current water-mist system. Based on the experiment analysis using a full-scale KHV system, the water-mist recirculation system has great potential and improvement to the current system operation. From the emissions sampling data, the recirculation system filters the grease emissions as well as the current water-mist system with the same water-mist spray viscosity at 0.7 *cP*. There are significant effects on water consumption and operational cost reductions. The water-mist recirculation system is also able to reduce the temperature inside the plenum and ductwork and recorded the same effect with the current water-mist system using fresh cold water. The most important factor is water cost and water consumption to the user. By adopting the recirculation system to the current water-mist kitchen hood, the operational cost is reduced. From the analysis conducted, the user could save up to RM 6,977.86 per year (1405.07 eur/year) per hood length for water cost. It is an 87.50 percent of water cost reduction for all U.S, European, and Asian kitchen hood designs. The water consumption can be saved up to

611,667 litres per year and 466,798.5 litres per year water for all U.S, European, and Asian kitchen hood designs per hood length.

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References

[1] Abdullahi, Karimatu L., Juana Maria Delgado-Saborit, and Roy M. Harrison. "Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: A review." *Atmospheric Environment* 71 (2013): 260-294. https://doi.org/10.1016/j.atmosenv.2013.01.061

[2] Lee, Jun-Bok, Ki-Hyun Kim, Heung-Joo Kim, Seog-Ju Cho, Kweon Jung, and Shin-Do Kim. "Emission rate of particulate matter and its removal efficiency by precipitators in under-fired charbroiling restaurants." *TheScientificWorldJOURNAL* 11 (2011): 1077-1088. https://doi.org/10.1100/tsw.2011.103

[3] Whynot, Jill, Gary Quinn, Pamela Perryman, and Peter Votlucka. "Control of fine particulate (PM2. 5) emissions from restaurant operations." *Journal of the Air & Waste Management Association* 49, no. 9 (1999): 95-99. https://doi.org/10.1080/10473289.1999.10463886

[4] Kuehn, T. H., B. A. Olson, J. W. Ramsey, and J. Rocklage. "Characterization of effluents from additional cooking appliances. Final Report, ASHRAE 1375-RP." *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta* (2008).

[5] Livchak, Andrey, Derek Schrock, Matti Lehtimaki, and Aimo Taipale. "The facts about mechanical grease filters." *ASHRAE journal* 45, no. 6 (2003): K14.

[6] Asmuin, Norzelawati, Mohd Farid Sies, Mohamad Khairi Hassan, M. R. Pairan, N. A. Nor Salim, and H. Zakaria. "Simulation of water mist spray for commercial kitchen ventilation (CKV) system using Ansys-CFD." *Applied Mechanics and Materials* 660, (2014): 704-708. https://doi.org/10.4028/www.scientific.net/AMM.660.704

[7] Gerstler, W., T. Kuehn, D. Pui, J. Ramsey, M. Rosen, R. Carlson, and S. Petersen. "Identification and characterization of effluents from various cooking appliances and processes as related to optimum design of kitchen ventilation systems." *Final report, ASHRAE* (1999).

[8] Abed, A. H., Shcheklein, S. E., & Pakhaluev, V. M. Experimental investigation in improving thermal performance of passive heat removal system using mist assisted evaporative cooling. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 69*, no. 1,(2020): 98-109. https://doi.org/10.37934/arfmts.69.1.98109

[9] Dziegielewski, et.al. (2010). "Saving Water in Restaurants". Retrieved March 29, 2018, from www.epa.gov/watersense/commercial.

[10] Stephane, C. "Waterwash & Watermist Optimized Control Cabinet with Recirculation System& Detergent Optimisation (Pre-study)". *Lab Measurement, Halton R&D Bethune, France,* (2013).

[11] Li, Zhouhang, Yuxin Wu, Hairui Yang, Chunrong Cai, Hai Zhang, Kazuaki Hashiguchi, Keiji Takeno, and Junfu Lu. "Effect of liquid viscosity on atomization in an internal-mixing twin-fluid atomizer." *Fuel* 103 (2013): 486-494. https://doi.org/10.1016/j.fuel.2012.06.097

[12] Yao, Shanshan, Ji Zhang, and Tiegang Fang. "Effect of viscosities on structure and instability of sprays from a swirl atomizer." *Experimental Thermal and Fluid Science* 39 (2012): 158-166. https://doi.org/10.1016/j.expthermflusci.2012.01.020

[13] Farid, S. "Development of Deflector Flat Spray Nozzle With Mixed of Water and Organic Citric Acid For Emissions Trap and Cooling In The Kitchen Hood Ventilation System". *Ph.D Thesis. Universiti Tun Hussein Onn Malaysia*, (2018).

[14] Livchak, Andrey, Derek Schrock, and Zeqiang Sun. "The effect of supply air systems on kitchen thermal environment." *Ashrae Transactions* 111, no. 1 (2005): 748-754.

[15] Hotelier, G. "Energy Efficiency In The Kitchen".(2010)

[16] Ziane, Rabah. "Halton design guide for indoor air climate in commercial kitchens." *Halton foodservice* (2007).

[17] Kamsah, Nazri, Haslinda Mohamed Kamar, Muhammad Idrus Alhamid, and Wong Keng Yinn. "Impacts of temperature on airborne particles in a hospital operating room." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 44, no. 1 (2018): 12-23.

[18] Kamar, H. Mohamed, N. Kamsah, KNA Ku Shuib, and N. A. Mufid. "Performance Analysis of a Solid Desiccant Air Dehumidifier." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 10, no. 1 (2015): 5-10.

[19] ASTM 2519-05. (2005). Standard Test Method for Grease Particle Capture Efficiency of Commercial Kitchen Filters and Extractors. ASTM International, West Conshohocken, PA 19426-2959. United States.

[20] ANSI/UL 1046. (2010). Standard for Safety for Grease Filters for Exhaust Ducts. Fourth Edition.

[21] American society of heating, refrigerating and air-conditioning engineers (ASHRA). *Method of Testing General Ventilation Air-cleaning Devices for Removal Efficiency by Particle Size: Standard 52.2-2017 (Norme)*. ASHRAE, 2017.

[22] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE - 2007). ASHRAE Handbook-HVAC Applications (SI): Kitchen ventilation. ASHRAE: Kitchen Ventilation: Chapter 31.

[23] Handbook, A. S. H. R. A. E. *HVAC systems and equipment*. Vol. 39. chapter, 2016.

[24] ASHRAE. (1999). HVAC Applications Handbook.

[25] Richter, Christian Paul, and Rainer Stamminger. "Water consumption in the kitchen–a case study in four European countries." *Water resources management* 26, no. 6 (2012): 1639-1649. https://doi.org/10.1007/s11269-012-9976-5

[26] Sayinci, Bahadir. "Effect of strainer type, spray pressure, and orifice size on the discharge coefficient of standard flat-fan nozzles." *Turkish Journal of Agriculture and Forestry* 39, no. 5 (2015): 692-704. https://doi.org/10.3906/tar-1410-89

[27] Yao, J. F., K. Tanaka, A. Kawahara, and M. Sadatomi. "Design Procedure and Performance Evaluation of a Flat-Jet Twin-Fluid Atomizer by Siphoning Liquid." *IACSIT International Journal of Engineering and Technology* 7, no. 5 (2015).

[28] Zhao, Yujiao, Angui Li, Ran Gao, Pengfei Tao, and Jian Shen. "Measurement of temperature, relative humidity and concentrations of CO, CO_2 and TVOC during cooking typical Chinese dishes." *Energy and buildings* 69 (2014): 544-561. https://doi.org/10.1016/j.enbuild.2013.11.037