Case Study: Heat Recovery and Demand Controlled Ventilation in Industrial Kitchens

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ABSTRACT

Industrial kitchens have high HVAC load requirements due to high exhaust rates from hoods. Especially in cold climates to heat the makeup air in winter requires high initial and - more importantly - high operating costs. Heat recovery always looks like an attractive alternative due to the high temperatures of hood exhaust air. However, since hood exhaust is quite dirty, heat recovery sections are clogged very fast. Heat recovery systems are established in six restaurants in Ankara, Turkey. Hood exhaust lines equipped with electrostatic precipitators (ESP) to keep heat recovery coils clean. Two of those six installations have ESP's with self-cleaning automatic washing systems and operating successfully. Four other installations have ESPs without self-cleaning automatic washing systems and clogged very fast. One of the successfully operating systems has temperature based demand control. The other one has manual fan speed control. Makeup air side fan speeds are interlocked with exhaust fan speeds. This study will show ESP's with automatic washing system protects heat recovery sections and discuss the equipment, methods, results of the installed systems and user behaviors including maintenance and operation.

BASIC CONSIDERATIONS

Besides the cooking activities, exhaust air and makeup air requirements increase the energy consumption rate of the industrial kitchens. To drop energy consumption, first attempt may be to decrease the exhaust flow rate and consequently the makeup airflow rate. Excess airflow rate increases both fans' power consumptions and makeup air treatment consumptions and must be avoided strictly.

First, the appropriate hood exhaust flow rate calculation method shall be chosen. Even almost all systems use VSD, exact sizing of ducts and fans are crucial. Because minimum duct velocities are limited to 2.54 m/s (7.9 f/s). If ductwork is oversized, air velocities may drop below 2.54 m/s (7.9 f/s) during partial load operations. Improper flow rate calculation can make the low duct velocity limitation is the lowest operating point, while lower flow rates could fulfill the hood requirements for good capture.

Required exhaust flow is directly proportional to heat generated by the cooking appliance. If the cooking appliance generates more heat, the required exhaust rate is more. So, flow rate calculations, which are based on heating capacities, surface temperatures, surface area of appliances and considering empty desks and hood geometry give better results.

Hood geometry and placement, location of appliances under the hood and makeup air supply patterns also affect the flow rate.

Deeper hoods with overhangs, side panels and rear seals give better performance. Placing heavy duty appliances in the middle of the hood should be preferred.

Makeup air supply effects hood performance. Makeup air supply methods show difference between conditioned and unconditioned air supply. While a back wall supply plenum is better for unconditioned air supply, a perforated ceiling is best for conditioned air supply. For either conditioned or unconditioned air supply four-way diffusers are not a good choice.

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While trying to decrease exhaust and consequently makeup airflow rates, one should keep in mind that exhaust air temperatures are better below 40°C (104°F). If the temperature gradient between exhaust air and duct wall increases more accumulation occurs on the duct wall which increases pressure loss, increases maintenance requirements and more importantly increases the fire risk. Above 40°C (104°F) exhaust temperatures, the efficiency of electrostatic precipitators and activated carbon filters drop. So, it is better to decrease flow rates, but exhaust air temperature and duct velocity are the limits that we must pay attention.

After required exhaust rates are calculated, energy conversation alternatives, one of which is subject of this article, must be avaluated.

ASHRAE Standard 90.1 states that any commercial kitchen ventilation system with total exhaust airflow rate greater than 8.640 m3/h (5.085 cfm) must contain one of the following:

1- 50% of the kitchen makeup air must be transferred air which would otherwise be exhausted.
2- A heat recovery system with efficiency not less than 40% on at least 50% of exhaust air.
3- A demand controlled ventilation system on at least 75% of the exhaust air. This system must be capable of reducing 50% of the exhaust and accordingly the makeup airflow rates.

International Mechanical Code prohibits heat recovery systems on commercial kitchen exhaust systems, except the application of ERV equipment that recovers sensible heat only utilizing coil-type heat exchangers.

SYSTEM DESCRIPTIONS

Heat recovery installations in six restaurants' hood exhaust lines are explained below briefly. All systems have ecology units, which are consist of electrostatic precipitators and activated carbon filters, before heat recovery sections to protect heat recovery sections from oil and smoke plume.

1- A 5.000 m3/h (2.942 cfm) flow rate exhaust line equipped with a plate type heat recovery. Outside fresh air passed through heat recovery is given to the dining hall. The ceiling of the dining hall is quite high. Fresh air is distributed slowly at the highest level of the ceiling freely. The ceiling is fully open and all surfaces and equipment are painted black. Ceiling type fan coils get air by free return and supply by slot diffusers.

The kitchen hood exhaust fan has a VSD. The fresh air supply fan has a constant flow to cover dining hall hourly air changes. The kitchen makeup air is transferred through a service door between the dining hall and the kitchen. Fan coil units' capacities are able to handle whole cooling and heating loads including fresh air load without heat recovery. There is a central heating-cooling plant of the main building.

The ecology unit is installed in the kitchen ceiling.

2- A 7.500 m3/h (4.414 cfm) flow rate exhaust line equipped with a run around heat recovery system. A dedicated fresh air supply AHU supplies fresh air to ceiling type fan coil units installed in the dining room suspended ceiling gab. Each fan coil unit has a mixing box to mix fresh air and return air. All fresh air is given to dining hall. There are two hoods. One is open to the dining hall, after a service desk, the other one is in the kitchen. Kitchen makeup air goes through service door.

The exhaust fan has VSD and fresh air AHU has constant flow. The fresh air AHU has a secondary heating coil to heat fresh air. Secondary coil has a capacity to heat the fresh air without heat recovery. There is a central heating-cooling plant of the main building.

The ecology unit is installed in attic one floor above.

3- A 10.000 m3/h (5.885 cfm) flow rate exhaust line equipped with a run around type heat recovery. Heating and cooling loads of the restaurant are fulfilled by VRF system. Fresh air is distributed in suspended ceiling gab close to VRF concealed ceiling type indoor units. Suspended ceiling gap works like a big mixing plenum box. This restaurant is a fast-food restaurant. The kitchen is almost fully open to the dining hall. There is only a serving desk between the kitchen and the dining hall. So, all makeup air of the kitchen transferred from the dining hall.

In cold climates due to fresh air treatment, heating loads are much bigger than cooling loads. Since there isn't a central heating-cooling plant of the main building of this restaurant, selecting the VRF capacity to fulfill the entire heating load including the fresh air heating load without heat recovery would increase the initial equipment cost. So, the VRF system indoor and outdoor units installed capacities are not including the fresh air heating load without heat recovery.

The hood exhaust fan has a manually controlled VSD. The fresh air supply unit has a constant speed fan. The ecology unit is installed on the rooftop, the duct work route to ecology unit passes through the main building and a quite long route.

4- A 12.000 m3/h (7.062 cfm) flow rate exhaust line equipped with a run around heat recovery. An AHU with a mixing box is installed to fulfill the dining hall cooling and heating loads and supply fresh air. All air from AHU is given to the dining hall. The AHU's heating coil capacity is enough to take the entire heating load including the fresh air load without heat recovery. All air from the AHU is given to the dining hall. Half of the makeup air is transferred to the kitchen by a transfer fan from the dining hall. Other half of the makeup air goes through service door to keep pressure balance between the dining hall and the kitchen.

The hood exhaust fan and the kitchen transfer fan have VSDs. The transfer fan is driven in parallel with the hood exhaust fan. As the exhaust fan speed increases the transfer fan speed also increases.

Hood exhaust fan has a manual overdrive speed up control and temperature based demand control. Manual overdrive is done by a push button. Each push increases the fan speed by 5 Hz. As the exhaust fan speed increases, the transfer fan speed increases, the dining hall pressure differential drops and the mixing damper opens fresh air side. 10 minutes after the push button speed adjustment, a DDC records the exhaust instantaneous air temperature. Then, if the exhaust air temperature drops from the recorded value, the DDC decreases the exhaust fan speed. Consequently, the kitchen transfer fan speed decreases and the dining hall AHU mixing box damper takes more return air instead of fresh air.

The dining hall fresh air supply AHU has a constant speed fan. Because the supply air is given at a 4,5 mt. (15ft) height. If the flow rate drops, it is not possible to push the supplied hot air down to comfort zone level. The ecology unit is installed in the kitchen suspended ceiling with a catwalk.

5- A 14.000 m3/h (8.240 cfm) flow rate exhaust line equipped with a run around type heat recovery. The heat recovery water temperature difference is designed to be 5 °C (41°F). The fresh air is given to restaurant by three different AHUs.

First AHU is the kitchen makeup air AHU. The first AHU has only one heating coil which is fed from heat recovery. No additional heating source is used to heat the kitchen makeup air. The kitchen makeup air AHU has an evaporative cooling section. Since the hourly change rate of the kitchen is high enough, evaporative cooling is applied very successfully for the kitchen. In summer, 10°C (50°F) temperature drops are gained and kitchen comfort level increased.

Second AHU is a mixed air one for ventilation and heating needs of the dining hall. A preheating heat recovery coil is installed before the mixing box of dining hall AHU.

Third one is a duct type split A/C unit which serves to offices. A preheating coil fed from heat recovery is installed before split A/C.

The dining hall AHU and the office split A/C have constant flow rates. The kitchen AHU has a VSD and its speed is interlocked with the hood exhaust fan speed. The exhaust fan speed control is manual by a VSD. The fresh air side fan VSD is driven by a DDC. DDC controller allows us to multiply the manually adjusted control voltage of hood exhaust fan VSD with a multiplier to set fresh air fan VSD control voltage to adjust the pressure difference between the kitchen and the dining hall. Fresh air given to dining hall goes to the kitchen through a service door.

This restaurant has an automatic washing system for electrostatic precipitator. The automatic washing system washes the ESP every night.

This restaurant built up its own heating plant room. A 100 kW condensing boiler is used to heat 720 m2 (7.750 ft2) restaurant area, hot water supply to the kitchen and final heating of fresh air supply to the dining hall. Total 15.000 m3/h (8.828 cfm) fresh air is supplied and required fresh air heating capacity would be 108 kW, if a heat recovery was not installed. An additional boiler would be required, in a larger plant room.

The ecology unit is installed on the restaurant first floor.

6- A 12.000 m3/h (7.062 cfm) flow rate exhaust line equipped with a run around heat recovery. The heat recovery water temperature difference is designed to be 19°C (66°F). A dedicated fresh air AHU has a preheating coil fed from heat recovery, a cooling coil and a secondary heating coil. This restaurant is in a shopping mall and its exhaust rate is more than assumptions made during initial load calculations of the shopping mall. Due to load comes from unpredicted fresh air; heating energy given from the central heating plant is not enough to fulfill the actual heating requirement. As a result, for this application heat recovery is a lifesaving choice. Without heat recovery to reach the required comfort level is not possible. Also, this restaurant belongs to the same chain of forth restaurant. The owner of the chain restaurant requested to use heat recovery with automatic washing ESP and demand controlled ventilation. All the fresh air is given to the dining hall above the perimeter windows. Half of the makeup air for kitchen transferred by a transfer fan and the other half comes through service door. Since perimeter windows are at the opposite of the kitchen, the dining hall has a good fresh air distribution.

The kitchen hood exhaust fan is controlled by demand controlled automation. This automation allows the user overdrive the exhaust fan speed manually. User may adjust the flow rate by a touch screen that shows current speed on a slide bar. This slide bar is big enough to be seen from every corner of the kitchen. The automation controls the fan speed by a logic based on temperature of exhaust air. If the exhaust air temperature is higher than a previously set value, fan speed increases. If the exhaust air temperature value is lower than the preset value, fan speed decreases slowly. At the same time the fresh air AHU fan and the kitchen makeup air transfer fan are driven parallel. The kitchen makeup air transfer fan is driven by the same control voltage of the kitchen hood exhaust fan. The fresh air AHU fan is driven by a multiplied voltage.

Temperature based fan speed control brings fire mitigation advantages. As the exhaust temperature increases, by increasing the flow rate from the hood, duct surfaces are kept at lower temperatures. If a certain temperature value is passed, alarm or firefighting scenarios start.

Some control algorithms and alarm functions are added to the automatic washing system. The ecology unit is installed in mezzanine in the restaurant.

RESULTS

1- The system is installed in 2011. Before winter, the system was clogged and after a short while the restaurant was closed. It is a good example that showed plate type heat exchangers are almost impossible to clean.

2- The second and third restaurants didn't pay attention to maintenance of any HVAC equipment. After a short time from startup, both restaurants removed the electrostatic filter cells and the activated carbon filter cartridges. Because they were clogged and caused high pressure losses and decreased the hood exhaust rate. And finally, they removed the heat recovery sections.

3- The third restaurant's heat recovery section also clogged. User turns off the fresh air supply in very cold days because the VRF unit capacities are not enough to heat fresh air supply.

These three restaurants couldn't operate the systems even for a year. Not only heat recovery but electrostatic filters couldn't operate. Because restaurant crew couldn't perform regular maintenance works.

4- The fourth restaurant's ventilation and the heat recovery system installed in 2013. This restaurant was very good at electrostatic precipitator maintenance in the first year. A dedicated technician washed electrostatic precipitator cells once in every two days. After the first year, the activated carbon filter cartridges and the heat recovery coil were quite clean the heat recovery was successful. However, in the second year instead of restaurants own technician, main building's maintenance team got the duty and washed the ESP cells once in a week. During summer, before the second winter the heat recovery coil became dirty. Restaurant management couldn't keep the coil clean again. Heat recovery efficiency dropped and before the end of winter the heat recovery circulation pump was shut down by the restaurant management.

The dirty heat recovery coil after the second year is shown in fig.1 (a). Temperature sensor on exhaust line is covered by oil. As a result, its DCV (Demand Control Ventilation) reaction time got longer and temperature based DCV is not responding fast like it was acting in the first year, but still working. The restaurants management was happy with the results. Because even the heat recovery system is not operating after the first year, demand controlled ventilation is still working. This is a chain restaurant. When they compare the electricity consumption of different restaurants, this one has the lowest ratio. For the first year, they compared the heating consumptions, and this branch heating consumption ratio was lower than the others.

In the first year heat recovery worked quite well. The system could reach 21°C (70°C) preheat air temperatures while outdoor temperatures are around 0°C (32°F) and exhaust temperature is around 40°C (104°F).

a) b)

Figure 1. (a) Heat recovery coil after 2 years, without automatic washing system, (b) Heat recovery coil after 4 years with automatic washing system.

5- The fifth restaurant's system installed in 2014. It has an automatic washing system for ESP.

Instantaneous outdoor temperature, exhaust air temperature, heat recovery water temperature, kitchen supply air temperature (AHU1), dining hall supply air preheating temperature (AHU2) and VSD positions are measured and recorded. Data is given in Table.1. The photo of the heat recovery coil after 4 years is shown in fig.1 (b).

In many aspects this application is quite satisfactory. Six years passed; the kitchen supply air is heated only by heat recovery. Dining hall and office fresh air is preheated. Single 100 kW boiler is enough to fulfill required heating load including kitchen hot water supply.

Until the end of the fifth year the heat recovery coil was clean and quite efficient. After the fifth year, the electrostatic filter was failed. During summer the electrostatic filter didn't work and both activated carbon filter cartridges and the heat recovery coil became dirty and clogged. Before winter the electrostatic filter is activated, activated carbon filters are replaced and the heat recovery coil is cleaned. The heat recovery coil has a drain pan. So it is cleaned in the ecology unit and the cleaning was not very difficult and took about 3 hours. In the sixth year, the heat recovery efficiency was satisfactory like its previous years. After cleaning in fifth year no significant efficiency drop is observed.

While a remote connection to the system to record measurement values, it is seen that even the hood exhaust temperature is low, the exhaust rate is at maximum. The outdoor temperature is -1,6°C (29°F) and the kitchen supply air temperature is 11°C (52°F). Instead of decreasing hood exhaust flow, user preferred to decrease fresh air supply fan speed by changing VSD driving voltage multiplier. And kept hood exhaust fan speed constant, 100%.

After one hour of observation, the exhaust flow rate is decreased manually. Consequently, the exhaust temperature, the heat recovery coil leaving water temperature and the makeup air temperature are increased. At the same outdoor temperature of -1,5°C (29°F) a higher hood exhaust air temperature of 2,8°C (37°F) is achieved, the heat recovery leaving water temperature increased by 3,3°C (38°F) and the supply air temperature increased by 5,1°C (41°F) to 16,1°C (60,9°F).

These two measurements are taken almost at the same time. The cooking activity under the hood is almost the same, idle hours.

After then, some control parameters are taken to password protected levels. The restaurant crew informed about the case. It took a long time to teach to the kitchen crew how to use the fan speed control.

In summer, the cooling requirement increases as the cooking activity increases, mainly due to radiative heat transfer from the cooking surfaces. In summer, since evaporative cooled air raised comfort level in the kitchen, the fan speed is set to 100% always. In summer, both the exhaust and the makeup air fans operated at maximum continuously.

In Table 1, the dining hall fresh air supply AHU preheat temperatures are also given. The run around type heat recovery gives chance to use recovered energy in different AHUs.

The automatic washing system gives good results to keep the heat recovery coil clean; however, keeping the automatic washing system operational requires attention, too. The kitchen crew don't follow the detergent level and hot water temperature etc. properly.

Table 1. Fifth Restaurant's Data

Outdoor Temp. °C/°F	Exhaust Air Temp. °C/°F	HR W.Temp. °C/°F	AHU1 Supp. Air Temp. °C/°F	AHU2 Preheat Air Temp. °C/°F	Exhaust Fan VSD's %	Makeup A. AHU1 VSD's %
-9,8/14,3	27,4/81,3	18,5/65,3	12,7/54,8	6,1/42,9	58	58
-5,5/22,1	29,2/84,5	21,2/70,1	15,8/60,4	9,4/48,9	60	60
-5,2/22,6	27,5/81,5	19,9/67,8	14,1/57,3	8,2/46,7	60	60
-1,6/29,1	25,0/77,0	16,9/62,4	11,0/51,8	11,2/52,1	100	40
-1,5/29,3	27,8/82,0	20,2/68,3	16,1/60,9	13,0/55,4	61	24
2,1/35,7	28,5/83,3	21,5/70,7	18,3/64,9	15,4/59,7	58	23
2,1/35,7	34/93,2	20,8/69,4	15,7/60,2	217,1/62,7	38	29
5,1/41,1	28,2/82,7	18,7/65,6	13,7/56,6	15,8/60,4	48	44
5,3/41,5	29,4/84,9	20,3/68,5	16,2/61,1	15,4/59,7	31	34
8,0/46,4	27,9/82,2	21,1/69,9	15,3/59,5	13,0/55,4	100	70
8,5/47,3	32,9/91,2	24,1/75,3	16,0/60,8	20,6/69,1	87	73
14,1/57,3	37,8/100,0	36,3/97,3	31,2/88,1	25,9/78,6	100	100
14,7/58,4	32,9/91,2	25,2/77,3	20,9/69,6	21,0/69,8	58	50

6- The sixth restaurant's system installed in 2019. It has an automatic washing system for ESP.

Instantaneous outdoor temperature, exhaust air temperature, heat recovery water temperature, supply air temperature (AHU1) and VSD positions are measured and recorded. Data is given in Table.2.

In the year 2019, minimum outdoor temperature recorded in Ankara city center during restaurants' operating hours is -5°C (23°F). At -5°C (23°F) outdoor temperature heat recovery heated the outside fresh air up to 10°C (50°F).

In Table 2. Two different operating conditions at -5°C (23°F) outdoor temperature are shown. The last line shows acting of a fire mitigation scenario. The preset operating exhaust air temperature for this restaurant is 40°C (104°F). To catch 40°C (104°F) exhaust temperature, exhaust fan VSD control voltage increased the fan speed over maximum set values. And 40°C (104°F) temperature is reached at 115% speed. At this point fresh air preheated temperature is 7°C (45°F).

The other record at -5°C (23°F) outdoor temperature, the exhaust temperature is 31°C (88°F) and the exhaust fan speed is 50%. Since the exhaust air temperature is below 40°C (104°F) preset value, the fan speed is decreased down to 50%. Due to minimum duct velocity and adequate dining hall and kitchen ventilation 50% fan speed is the bottom line for this restaurant. As the fan speeds decreased and fresh air amount decreased, thought exhaust temperature 31°C (88°F) is lower than 40°C (104°F), supply air preheat is increased to 10°C (50°F) instead of 7°C (45°F).

In Table 2, there are 2 records at 0°C (32°F) outdoor temperature. One of the records is taken while the exhaust air temperature is 39°C (102°F), the exhaust fan speed is 90% and the fresh air fan speed is 28%. The preheat supply air temperature is 17°C (63°F). The second record is taken while the exhaust air temperature is 35°C (95°F), the exhaust fan speed is 67% and the fresh air fan speed is 41%. At this time the preheat supply air temperature is 10,6°C (51°F). While the exhaust air temperature difference is 4°K, the supply air preheat temperature difference is 6,5°K.

These four records show decreasing the flow rates gives higher supply air preheat temperature values.

This restaurant's run around coil heat recovery system is designed according to 19°C (66°F) water temperature difference, to decrease coil water side pressure drops. However, if we compare the results with the system established according to 5°C (41°F) water temperature difference, the 19°C (66°F) difference system has lower efficiency.

After the first year passed this restaurant's automatic washing system showed better performance by added alarm features and LCD screen interface. The heat recovery coil is as clean as it was first day.

Table 2. 6th Restaurant's Data

Outdoor Temp. °C/°F	HR Coil Air Inlet Temp. °C/°F	HR Coil Water Outlet Temp. °C/°F	AHU 1 Preheat Air Temp. °C/°F	Exhaust Fan VFD's %	Makeup Air AHU 1 VFD's %
8/46	37/98	32/90	19/66	73	23
3/37	39/102	34/93	16/61	75	24
0/32	39/102	35/95	17/62	90	28
0/32	35/95	30/85	11/51	67	41
-5/23	31/87	26/78	10/50	50	32
-5/23	40/104	33/92	7/44	115	71

CONCLUSIONS

As IMC states, the run around coil heat recovery system must be preferred. Cleaning a dirty heat recovery coil is not very difficult and the first day efficiency can be almost achieved. The Run around coil heat recovery gives chance to use recovered heat in different AHUs' preheating coils and flexible designs.

The ecology units should be installed as close as possible to the kitchen. Ecology units installed on the rooftops or in the attic are more difficult to maintain. ESP units installed close to the exhaust hood protect ducts from grease accumulation.

For heat recovery systems installed in kitchen exhaust lines maintenance is vital. Electrostatic precipitators are good choice to protect the heat recovery coil. However, without an automatic washing system the electrostatic precipitators are also hard to maintain.

The restaurant crews are not familiar with HVAC maintenance works and operation. Dedicated technicians or automatic washing system is required. Automatic washing systems give satisfactory results. Both, the HVAC and the automatic washing systems must be equipped with strong automation features to minimize experienced personnel requirement.

The fan speed must be controlled by an automation system. The restaurant crew tends to have always maximum hood exhaust flow. Working with demand controlled automatic fan speed is hardly accepted by the restaurant crew. So, user friendly, wide screen, easily visible control interface gives better results. However, some system operating parameters must be protected by passwords.

If possible, the preheating coil should be installed before the mixing box of AHU. Since the mixed air temperature is increasing, the heat recovery efficiency is decreasing.

In cold climates besides lower operating costs, even first installations costs can be lower by using a heat recovery system, like the third restaurant which is using the VRF system to heat fresh air.

At no cooking activity condition, the hood exhaust air temperature drops. By using demand controlled fan speed automation, fan speeds are decreased and exhaust temperature is held relatively high enough to heat the makeup air. Since makeup airflow is decreased at the same time heating load also decreases and makeup air temperature stays satisfactory. In addition, makeup air velocity in kitchen drops and cold air velocities doesn't create discomfort. If we expect restaurant crew to decrease flow rates, they don't decrease, unfortunately.

The run around coil heat recovery systems with lower water temperature differences give better efficiency.

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