Determination of the Annual Energy Consumption by the Ventilation Systems of the Restaurant’s Kitchen

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Abstract. The purpose of the article is to assess the impact of each of the methods used by engineers for calculating air exchange in a hot kitchen workshop on the energy consumption of ventilation systems. The calculation was carried out using six methods for determining the air flow rate removed by local kitchen hoods. For computer modeling of energy consumption, a probabilistic-statistical climate model and a universal PC program were used. which has been built according to the data of primary observations at the Moscow weather station for 30 years. The repeatability of combinations of the climate parameters is given for the cells with a 2 °C temperature step and a step of 5 % of the relative humidity. The content of the model represents a table of 19x37 cells.

Significant discrepancies in the results of calculating exhaust hoods using different methods determine the need for experimental research and the creation of a generalized method. The efficiency and economy of its operation depends on the choice of the method for calculating the exhaust hood. Since the polluted air removed by local kitchen hoods must be compensated for, the air handling unit is forced to clean and warm up huge volumes of air, which increases both the capital costs of equipment and operating costs for the consumption of electricity, heat/cold. The discrepancy in energy consumption by supply and exhaust ventilation units operating in a ranges: from 6 to 97 % for electricity, from 6 to 63 % for heat, from 14 to 30 % for cold.

1. Introduction

Hot shop ventilation is a multi-component system that takes into account various factors in the arrangement of the kitchen space. It is a fact that a lot of heat and gas is generated during the cooking process in commercial kitchens. The resulting heat surplus must be promptly removed from the premises using ventilation systems in order to: maintain comfortable working conditions for personnel in accordance with SanPiN 2.2.4.548-96; comply with the technological process of cooking culinary products; maintain the conditions of the microclimate of the room to comply with fire safety rules.

Local ventilation of the hot shop of a public canteen is represented by exhaust hoods installed above the heating equipment. The main function is to remove the warm exhaust air flow (including odors, smoke, oil, etc.) from the working area by creating an additional area of rarefied pressure. When designing a kitchen ventilation system, the main indicator is the air flow through the exhaust hood. Low air flow rates can disrupt the function, causing polluted air to spread throughout the room. Excessive air consumption leads to unnecessary costs, both capital and operating ones. However, an increase in the amount of exhaust air means an increase in the amount of supply air. A problem of
It is possible to apply a part of the supply air to the 23600 v or stable operation 0.2 characteristics of the SER ∙ = = LS = 3600 v A n 64 gases is proportional to the area of the heat source, m equipment to local suction, 1.1 m; flow temperature of 70°C or more, depending on the flow rate of air rate of the removed air example, the actual heat load (more precisely, the proportion of convection) is neglected. from the edge of the umbrella to the radiating surface, m. of kitchen equipment; classification of the hot shop by type of cuisine; organization of air exchange inside the kitchen dimensions; type of following initial data are required: the type of kitchen equipment installed by the technologists and for ventilation of the hot shop and any options using secondary energy resources (SER). In cold climates, the heat from the exhaust air from the hood can be used to heat the supply air. However, measures must be taken to regularly clean the filters and maintain the heat exchanger to prevent it from clogging up with oil particles from the exhaust air, or use alternative cleaning methods [4-6].

2. Methods of investigations

Several methods proposed by domestic scientists for determining the air flow through an exhaust hood were considered in the process of designing an object - a restaurant in Moscow. The area of the hot shop is 35.9 m², the volume is 143.6 m³. The technologists provide an island range hood with dimensions of 3100x1600x400 mm. The standard installation height of the exhaust hood above the surface of the clean floor is 2 m [7].

In the hot shop, an exhaust is provided, achieved by supplying a part of the supply air to the adjacent food delivery room (is taken as 30 % of that removed by the local suction), which is intended for ventilation of the hot shop and flowing through the opening, since it is technologically impossible to provide overflow from the dining room.

To calculate the exhaust air flow rate through local suction (LS) in the applied methods, the following initial data are required: the type of kitchen equipment installed by the technologists and its dimensions; type of a hood, height of its placement above the work surface; classification of the hot shop by type of cuisine; organization of air exchange inside the kitchen [8].

For many years, the method of suction rate has been used in Russian practice [9]:

\[ L_{LS} = 3600 v A \] (1)

where \( L_{LS} \) is the flow rate of air removed from the serviced area of the room by a local exhaust, m³/h; \( A \) - area of the design section of the umbrella, m²; \( v \) - is the required value of air speed for stable operation 0.15–0.3 m/s, depending on the size of the umbrella and the type of kitchen equipment.

An analogue of this formula in the materials [10] is "calculation by traditional methods":

\[ L_{LS} = 3600 v PH \] (2)

where \( v \) - is the required value of air speed for stable operation 0.2–0.5 m/s, depending on the type of kitchen equipment; \( P \) - is the perimeter of the horizontal projection of the umbrella, m; \( H \) - distance from the edge of the umbrella to the radiating surface, m.

In both cases, this method does not take into account the characteristics of the equipment, for example, the actual heat load (more precisely, the proportion of convection) is neglected.

When using a hood over a heated surface, the authors of the method [11] proposed to take the flow rate of the removed air on the basis of the presence of a stable convective flow that occurs at a temperature of 70°C or more, depending on the flow rate of air flowing to the hood with a convective flow:

\[ L_{LS} = 64 \sqrt{Q_c z F_s^2 \cdot \frac{F}{F_s}} \] (3)

where \( Q_c \) - convective heat from kitchen equipment, W; \( z \) - distance from the surface of kitchen equipment to local suction, 1.1 m; \( F \) - is the area of the suction section of the umbrella, m²; \( F_s \) - is the area of the heat source, m².

According to the method [12], the flow rate of air removed from the source that emits heat and gases is proportional to the “characteristic flow rate of air in the convective flow rising above the heat source”: common ventilation systems with constant air exchange value is the waste of energy by fans and air conditioners [1-3].

The purpose of the paper is to assess the impact of each of the methods used by engineers for calculating air exchange in a hot shop of a kitchen on the energy consumption of ventilation systems that maintain acceptable indoor microclimate conditions. Based on this calculation, it is possible to make a further financial assessment using the total discounted costs of both standard solutions for ventilation of a hot shop and any options using secondary energy resources (SER). In cold climates, the heat from the exhaust air from the hood can be used to heat the supply air. However, measures must be taken to regularly clean the filters and maintain the heat exchanger to prevent it from clogging up with oil particles from the exhaust air, or use alternative cleaning methods [4-6].
\[ L_{LS} = 945d^2 \cdot 0.068 \left( \frac{Q_c}{\rho \cdot c} \right)^{1/2} k_p k_c k_v \]  

where \( d \) - is the equivalent diameter of the source, m; \( k_p \) is a dimensionless factor that takes into account the influence of geometric and operating parameters that characterize the "source-suction" system; \( k_c \) - coefficient taking into account the influence of the speed of air movement in the room; \( k_v \) - is a coefficient that takes into account the toxicity of harmful emissions.

The paper [13] considers in detail the issues of calculating air exchange in the hot shop of public catering enterprises, both in terms of the productivity of local suction and the removal of excess heat. To calculate the air exchange in hot shops, the following are taken: the temperature of the air removed through hoods, curtains and localizing devices above the kitchen equipment that generates heat, is up to 42°C; air temperature under the ceiling is 30°C (according to TSN 31-320-2000 standards of Moscow).

The volume of air removed by local suction is determined by the formula [13]:

\[ L_{LS} = \frac{3600Q_{eq1}}{cp(42-t_{wa})} \]  

where \( Q_{eq1} \) - is the amount of heat supplied under the exhaust hood from the source, W; \( \rho \) - is the density of air removed by local ventilation, kg/m³; \( c \) - specific mass heat capacity of air equal to 1005 J/(kg·°C); \( t_{wa} \) - air temperature in the kitchen working area, °C.

Heat input from the technological equipment of kitchens \( Q_{eq1} \), W, was determined by the formula:

\[ Q_{eq1} = 1000K_s \sum_{i=1}^{n} N_{K_s}(1 - K_{LS}) \]  

where \( N \) - is the installed capacity of the process equipment (see Table 1), kW; \( K_s \) - coefficient of simultaneous operation of heating equipment (for restaurants - 0.7); \( K_t \) - load factor of heating equipment (electric stoves - 0.65; electric bain-marie and heating cabinets, electric pans and electric fryers - 0.5; other equipment - 0.3); \( K_{LS} \) - coefficient of efficiency of exhaust devices, equal to 0.75.

The air flow rate removed by local suction is determined based on the capture of the convective flow rising above the hot surface of the kitchen equipment. Air consumption in convective flow, \( L_{ci} \), m³/s, over individual kitchen equipment is calculated by the formula [14]:

\[ L_{ci} = k Q_{ci}^{1/3}(z + 1.7D)^{5/3r} \]  

where \( k \) - is the experimental coefficient equal to 5·10⁻³ m⁴/³·W⁻¹·s⁻¹; \( Q_{ci} \) - is the proportion of convective heat release from kitchen equipment, W; \( D \) - is the hydraulic diameter of the kitchen equipment surface, m; \( r \) - correction for the position of the heat source in relation to the wall, we take 1.

Local suction air flow rate:

\[ L_{LS} = \frac{\left( \sum_{i=1}^{n} L_{ci} \right) a}{K_{LS}} \]  

where \( n \) - is the number of equipment located under the suction; \( a \) - a correction factor that takes into account the mobility of air in the hot shop, when supplied through the plafond air distributors 1.2.

The calculation results using formulas (7) and (8) are summarized in Table 1.

**Table 1.** The results of calculating the air flow rate in the convective flow according to [14].

| Quantity, pcs. | Teppan Induction cooker | Ceramic cooker | VOK cooker | Combi steamer | Deep fryer |
|----------------|-------------------------|---------------|------------|---------------|-----------|
| Installed power, kW | 2 | 2 | 1 | 1 | 1 | 2 |
| Hydraulic diameter, m | 0.75 | 0.51 | 0.51 | 0.51 | 0.85 | 0.70 |
| Convective heat release, W | 840 | 245 | 560 | 350 | 350 | 297.5 |
Air consumption in convective flow \( L_s \), m\(^3\)/s

| Formula   | 0.186 | 0.088 | 0.117 | 0.100 | 0.156 | 0.123 |
|-----------|-------|-------|-------|-------|-------|-------|
| Total air flow rate removed from the umbrella \( L_o \), m\(^3\)/h | 6300 |

3. Calculation results

The air balance of the hot shop is determined on the basis of compensation for the air removed by local suction and general exhaust ventilation, taking into account the possibility of assimilation of heat inflows into the room. Calculation of air exchange in hot shops is carried out to absorb excess heat in the working area from people, electric lighting and technological heat equipment. The total heat input in the hot shop premises is 7.55 kW (1 kW from people, 0.46 kW from lighting, 6.1 kW from equipment according to the formula). The total moisture surplus was 3.15 kg/h, the heat-humidity ratio in the room was 8600 kJ/kg. The calculation is summarized in Table 2 for all considered methods.

Table 2. The results of calculating air exchange in the hot shop, taking into account the applied methodology for calculating LS.

|                                      | Formula (1) | Formula (2) | Formula (3) | Formula (4) | Formula (5) | Formula (8) |
|--------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Air consumption, removed by LS, \( L_s \), m\(^3\)/h (kg/h) | 5360        | 6340        | 3668        | 4833        | 3805        | 6300        |
| Air velocity at the entrance to the MO, m/s            | 0.3         | 0.63        | 0.21        | 0.27        | 0.21        | 0.35        |
| Air consumption, removed by general exchange hood, \( L_{ou} \), m\(^3\)/h (kg/h) | 300         | 355         | 300         | 300         | 800         |             |
| Air consumption flowing from the distribution room, \( L_c \), m\(^3\)/h (kg/h) | 1600        | 1900        | 1100        | 1450        | 1145        | 1890        |
| Supply air consumption, \( L_s \), m\(^3\)/h (kg/h) | 4000        | 4790        | 2815        | 3640        | 3425        | 4390        |
| Air exchange rate, 1/h                         | 39          | 80          | 28          | 36          | 32          | 44          |
| Supply air temperature during the warm period, °C | 22          | 24          | 20          | 22          | 22          | 24          |
| Air temperature in the working area during the warm period, °C | 26.4        | 25.9        | 26.6        | 26.8        | 26.9        | 27.0        |
| Exhaust air temperature under LS, °C          | 36.8        | 30.8        | 41.7        | 38.3        | 41.5        | 35.8        |
| Exhaust air temperature, °C                  | 29.4        | 28.9        | 29.6        | 29.8        | 29.9        |             |
| Supply air temperature during the cold period, °C | 16          | 16          | 16          | 16          | 16          | 16          |
| Air temperature in the working area during the cold period, °C | 21.9        | 20.0        | 23.5        | 22.3        | 21.5        | 21.4        |

The air exchange rate of the hot shop premises, according to the calculation, is 44 l/h. It exceeds 20 l/h. Therefore, the general exhaust ventilation is not required. For the previous methods, we will introduce certainty: two-fold general exhaust ventilation was adopted according to the recommendations of experts, for the general exhaust ventilation [13] - according to calculation.
The value of $Q_{eq2}$ according to [14] is determined similarly to $Q_c$ by the apparent heat release from the installed capacity of the equipment in the amount of 50%:

$$Q_{eq2} = \left(\sum_{i=1}^{n} (NK_{oh} n)\right) \cdot 0.5 \cdot k_o$$  \hspace{1cm} (9)

where $K_{oh}$ - is the share of obvious heat release from the installed power of kitchen equipment, W/kW; $k_o$ - coefficient of simultaneous operation of kitchen equipment, we take 0.7.

Consequently, the total heat input in the hot shop room is 6.16 kW (1 kW from people, 0.46 kW from lighting, 4.7 kW from equipment according to the formula. The total moisture surplus was 3.15 kg/h, the heat-humidity ratio in the room is 10600 kJ/kg. The calculation is summarized in Table 2 for all considered methods.

Following the general recommendation: the air temperature in the premises of hot shops with constant presence of people should be in the range from 16°C to 27°C. We will check that the air temperature in the working area is less than 27°C and no more than 5°C above the temperature outside air. If the temperature in the working area exceeds the permissible value, it is necessary to cool the air supplied by a separate air supply plant in order to maintain the set air temperature in the room.

We will also check the observance of the conditions that the air temperature under the hood at the ceiling $t_{out,ls} < 42°C$; air temperature under the ceiling $t_{out} < 30°C$ after calculating the air balance of the room, and the required value of the air velocity in the intake section of the exhaust hood is more than 0.25–0.3 m/s. The results of solving the balance equations [15-18] of the room are also summarized in Table 2.

For computer modeling of energy consumption and the amount of water consumed by central supply systems, a probabilistic and statistical climate model and a universal program have been developed at the HGV department of the NRU MGSU [19, 20]. The climatic base designed to analyze the operating modes of ventilation units, taking into account the operating time of the restaurant - 4970 hours per year, is a table in the cells of which the repeatability of combinations of temperature (with a gradation of 2°C) and relative humidity (with a gradation of 5%) are written down and the average atmospheric pressure for this combination is indicated. The calculation algorithm is based on enumerating combinations of temperature and relative humidity from minimum to maximum values. An air supply plant with heating of an outdoor air in the cold season and a controlled cooling process in a surface air cooler in the warm season has been adopted. The total flow rate of outdoor air processed by the central air supply plant takes into account the flow rate of supply air to the auxiliary rooms, which are served by the same system (4375 m³/h). The result of computer calculations for each option is presented in Table 3.

| Table 3. Annual consumption of electricity, heat and cold by supply air installation of the ventilation. |
|-------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Formula (1) | Formula (2) | Formula (3) | Formula (4) | Formula (5) | Formula (8) |
| Electric power consumed by the fan of the LS system, k\text{W\cdot h} | 4862 | 10129 | 3327 | 4384 | 3451 | 5714 |
| Electric power consumed by the fan of the general exchange exhaust system, k\text{W\cdot h} | 1039 | 1039 | 1039 | 1039 | 1493 | - |
| Heat consumption by the air heater of the air handling unit, k\text{W\cdot h} | 171010 | 278190 | 139804 | 161144 | 151489 | 182828 |
| Cooling consumption of the air handling unit, k\text{W\cdot h} | 4816 | -* | 6188 | 4176 | 3878 | -* |
| Electric power consumed by the fan of the general exchange inflow system, k\text{W\cdot h} | 3990 | 8312 | 2730 | 3597 | 2832 | 4689 |

* In these cases, the supply air temperature corresponds to the outside air temperature for the warm period with a supply of 0.95 (taking into account heating in the supply plant and the duct network) with a lack of air temperature exceeding the design values equal to 440 h/year.
4. Conclusion
Analysis of the results obtained in Table 2 and Table 3 shows that:
- none of the methods gave similar results within an error of 5–10%, in addition, the calculation by the formula gives results twice as high as the other approaches and a significant frequency of air changes, which allows us to question the application of this formula;
- the discrepancy in the air flow rates removed by the hoods ranges from 9 to 110 %;
- calculations by do not give the required value of the air velocity in the intake section of the exhaust hood more than 0.25–0.3 m/s;
- the discrepancy in energy consumption by supply and exhaust ventilation units operating in the hot shop ranges: from 6 to 97 % for electricity, from 6 to 63 % for heat, from 14 to 30 % for cold;
- as a result of calculations by, it is required to cool the outside air before supplying it to the hot shop in the warm season;
- as a result of calculations by, in the warm season, outside air can be supplied to the room without cooling, while the lack of air temperature does not exceed 200 h/year.

The efficiency and economy of its operation depends on the choice of the method for calculating the exhaust hood. Since the polluted air removed by local kitchen hoods must be compensated for, the air supply plant is forced to clean and heat huge volumes of air, which increases both capital costs for equipment and operating costs for the consumption of electricity and heat (cold). In addition, with the rise in energy prices, food service owners are also beginning to realize the benefits of using ventilation systems with the possibility of applying energy-efficient solutions. However, without a unified calculation methodology, it is impossible to assess the return on investment.

Significant discrepancies in the results of calculating exhaust hoods using different methods determine the need for experimental research and the creation of a generalized methodology based on these experiments.

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