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Energy Efficiency and Thermal Comfort: HVAC Design for an American Restaurant Environment

Abdullah Al Hossain Newaz*, Zheng Li

Department of Mechanical Engineering, University of Bridgeport, Bridgeport, USA
Email: *anewaz@my.bridgeport.edu

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Abstract

This paper represents the complete design of an HVAC system for an American Restaurant in Madison Wisconsin, especially focusing on balancing comfort, capability and cost-efficiency. A number of crucial factors are taken into account in the system design, such as duct size, airflow rates, heating and cooling loads, and weather conditions. To attain balanced pressure drops and ideal airflow distribution, the paper used the equal friction method for duct sizing. Building Drawings were created using Revit 2021 Software. Which helped with the accurate planning of diffuser and air handling unit (AHU) locations. In order to ensure compliance with industry standards, thorough calculations for pressure drops, ventilation needs, and thermal loads were carried out. The resulting HVAC system design shows a viable and successful solution for medium-sized restaurant buildings by efficiently managing energy flows, enhancing indoor air quality, and creating a comfortable environment for occupants.

Keywords

HVAC Design, Restaurant

1. Introduction

This paper examines the energy flow in buildings and the complexities of HVAC system design, highlighting important factors for effective and efficient thermal management [1] [2]. Energy flow, both positive and negative, comes from different places in a structure. Air temperature is determined by sensible heat, but humidity levels are affected by latent heat that comes from structures such as windows, roofs, and walls [3]. When ventilation or infiltration is combined with a temperature difference between the interior and outside air, heating or cooling must be provided; these losses or gains might be considered sensible or latent. Moreover, this complex energy interaction is facilitated by internal heat sources including equipment, people, and illumination. In the end, the HVAC system's heating or cooling load is determined by the total of these various energy flows.

Determining design loads often involves streamlining assumptions and modifying techniques to accommodate certain building kinds. For minor building heating loads, for example, steady-state techniques are sufficient; nevertheless, rapid fluctuations in sensible and latent loads are critical for air conditioning system size. A crucial component, meantime, is the methodical use of engineering concepts in duct design. In order to enhance HVAC system efficiency and ensure exact delivery of conditioned air to different zones, it looks for the best route for conditioned air, taking into account air velocity, pressure drops, and temperature properties [4].

Important duct design elements include pressure drop studies, friction loss computations, and using psychometrics to comprehend the thermodynamic characteristics of air. By following these guidelines, engineers can regulate temperature and humidity, maximize airflow dispersion, and improve indoor air quality [5]. The equal friction method, which is popular for commercial HVAC systems because it is easy to use and efficient for medium-scale to large-scale installations, will be the main topic of this paper [6].

2. Building Specifications

Maximum of 250 patrons (about 60 tables).

Cooking staff-6.

Waitpersons-10.

Hostess-1.

120 × 80 ft rectangular foundation, concrete slab-on-grade surface covered with indoor/outdoor carpeting.

3. Building Sketch Drawings

The building sketches have been done in Revit. It is a powerful Building Information Modeling (BIM) software that allows engineers and designers to create a comprehensive digital representation of the building's MEP.

The building area details in square feet are as follows (**Table 1**).

Table 1. Zone area data.

Zone	Floor Area (^{2})	Wall Area (^{2})	Window Area (^{2})	Maximum Occupancy
Kitchen-1	1500 ft	1200 ft	None ft	7
Gents Restrooms-2	180	400	None	10
Ladies Restrooms-3	180	400	None	10
Dining-4	2500	1568	None	136
Dining-5	1200	1088	None	72

Continued

Dining-6	800	892	36	52
Bar-7	1800	1348	60	100

Revit Software has been used to generate the Architectural drawing of the building as shown in the following photos [7] (**Figure 1** and **Figure 2**).

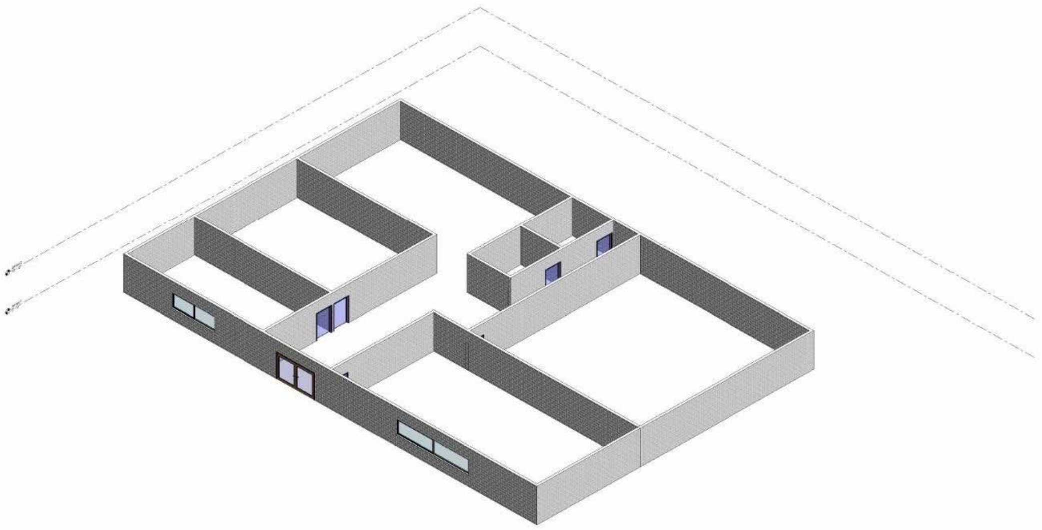
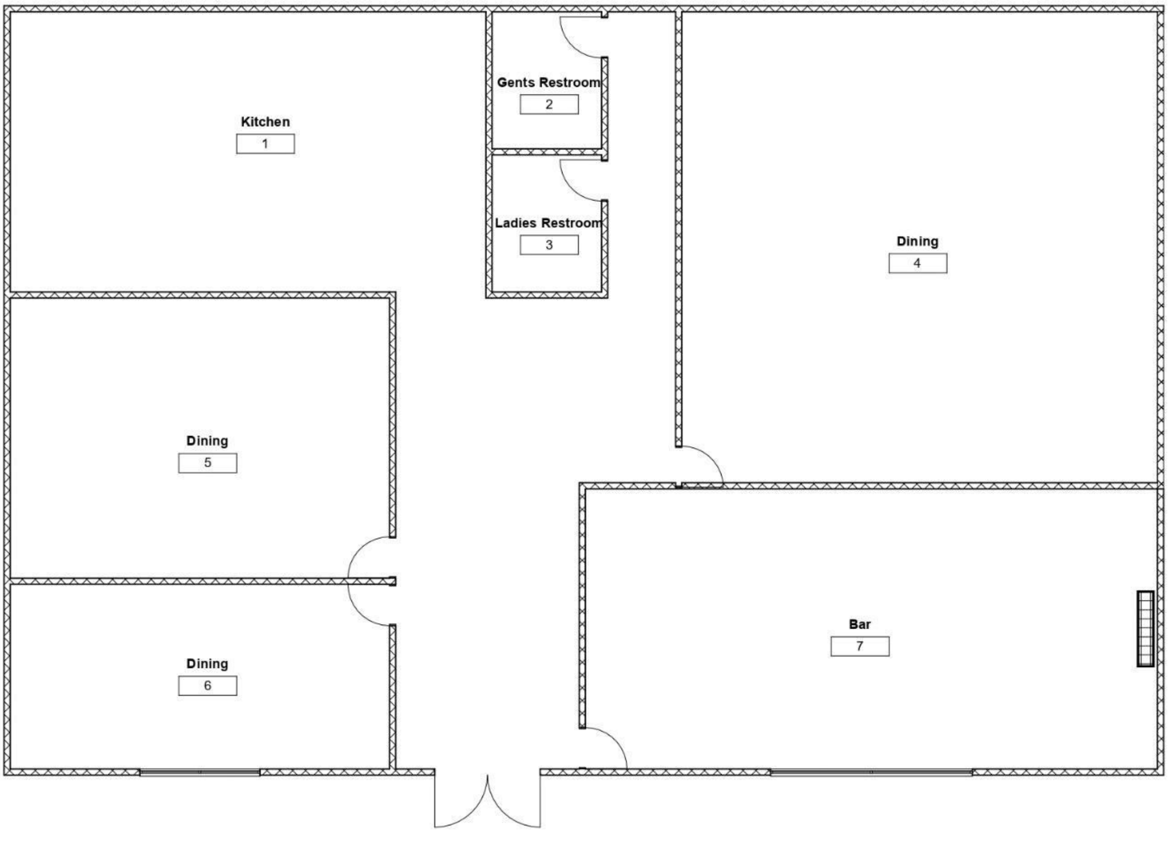


Figure 1. The building Floor plan, indicting the various rooms is shown below.



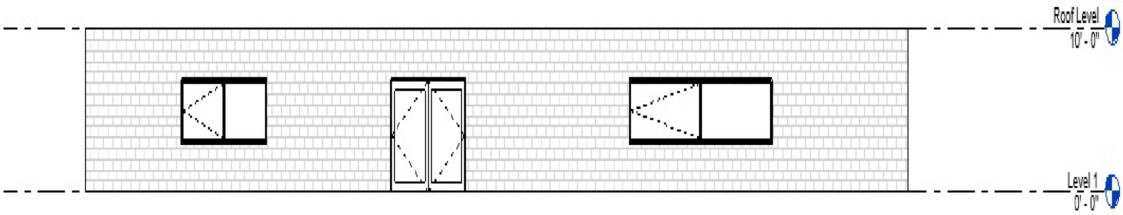


Figure 2. The front elevation (South) of the building is as follows.

4. Design Day Weather Conditions

Weather information that is used in design for locations in the USA and throughout much of the world is available in the ASHRAE Handbook, Chapter 14, "Climatic Design Information" (2009). Table A1 (English units) (see Appendix) is abstracted from this database and gives some of the basic design weather information for four USA locations.

For this project, the chosen design location is Madison, WI, with the following weather conditions:

Summer: 90˚F *db*, 73.7˚F *wb*.

Winter: −10.3˚F.

As shown in Figure A1 (see Appendix), the recommended temperature ranges are between about 67˚F and 76˚F (20˚C and 25˚C) for winter and between 74˚F and 82˚F (24˚C and 28˚C) for summer. The humidity range is less precise, and ranges from about 20% to 80% *RH*. The upper humidity limit of 80% reflects that people are uncomfortable when their skin feels damp, although an upper limit of 60% may be a better comfort level. The lower limit, corresponding to a humidity ratio of 0.044 lbm/lbm, is a level that dries out skin and makes one feel uncomfortable. The middle of the winter comfort range is 72˚F and 50% *RH*, and in summer is 77˚F (25˚C) and 50% *RH*. The conditions at the middle of the comfort range are often used in design calculations.

Therefore, the required interior design conditions are:

Summer: 77˚F and 50% *RH*.

Winter: 72˚F and 50% *RH*.

5. Building Heating and Cooling Loads

5.1. Design Heating Loads

Establishing the design heating load is essential for choosing equipment capable of sustaining the desired indoor temperature across all anticipated scenarios (Table 2). The calculation involves assessing envelope and ventilation/infiltration heat losses based on extreme weather records [8]. Typically, during this determination, assumptions are made, including the absence of solar gains through windows, negligible sol-air effects on walls and roofs, and no heat contributions from occupants, lights, or appliances [9].

Under these conservative assumptions, for each zone, or for the building as a whole, the heat loss, which is the heating load, can be expressed as (Table 3).

$$Lh = \sum \mathrm{Qe} \cdot i = \sum UAi\left(\mathrm{TZ} - \mathrm{TA}\right) \quad (1)$$

Formula 1 [10]

From Table A2, the thermal resistance for the various building components is:

Table 2. R values for various components.

Element	R-Value
Brick (4”)	0.4
Outside surface:	
Summer	0.25
Winter	0.17
Double glazing windows	1.6

The overall heat loss coefficient from each component is obtained as follows:

$$UAo = \sum UAi \quad (2)$$

Formula 2 [10]

From which the following is obtained:

Table 3. Heating loads for each zone.

Zone	*UAo* (BTU/hr-F)	*Lh* (BTU/hr)
Kitchen-1	480	39504
Gents Restrooms-2	160	13168
Ladies Restrooms-3	160	13168
Dining-4	627.2	51618.56
Dining-5	435.2	35816.96
Dining-6	414.4	34105.12
Bar-7	635.2	52276.96

5.2. Design Cooling Loads

Latent Cooling Loads

The windows and walls mainly deal with conductive loads. Heat from outside moves through these materials into space. If we’re only looking at conductive loads and not considering radiation or time, the only thing to think about is the heat transfer due to the temperature difference between outside and inside.

The cooling loads can be determined as follows:

$$AQc = UA\left(\mathrm{TA} - \mathrm{TZ}\right) \quad (3)$$

Formula 3 [10]

Using the building information and weather data, the following loads for each zone are obtained (Table 4).

Table 4. Wall/windows cooling loads.

Zone	*UAo* (BTU/hr-F)	*Lh* (BTU/hr)
Kitchen-1	480	6240
Gents Restrooms-2	160	2080
Ladies Restrooms-3	160	2080
Dining-4	627.2	8153.6
Dining-5	435.2	5657.6
Dining-6	414.4	5387.2
Bar-7	635.2	8257.6

6. People

The amount of heat a person gives off depends on how active they are. ASHRAE has a table in their Fundamentals guide that lists these heat values for both sensible (Table 5) and latent heat gains based on activity. You can calculate the total heat load from people by using these values, the number of people, and a cooling load factor, as shown in the equation below:

$$Qc = N \times \text{SHG} \times \text{CLF} \tag{4}$$

Formula 4 [11]

Where:

N = Number of People.

SHG = Sensible Heat Gain, Activity dependent.

CLF = Cooling Load Factor.

The cooling load factor takes into account the time lag factor and if it is not given it should be assumed to be 1.0. Using the data obtained from ASHRAE on Heat gain (Table A4), the following loads are obtained:

Table 5. Sensible heat gains per zone.

Zone	Maximum Occupancy	Heat Gain (BTU/h)
Kitchen-1	7	1790
Gents Restrooms-2	10	2559.1
Ladies Restrooms-3	10	2559.1
Dining-4	136	34803.8
Dining-5	72	18425.6
Dining-6	52	13307.4
Bar-7	100	30709.3

The total cooling loads for each zone are sum of the latent and Sensible heat loads calculated above (Table 6).

Table 6. Design cooling loads.

Zone	Latent Heat Gain (BTU/hr)	Sensible Heat Gain (BTU/h)	Total Cooling Load (BTU/hr)
Kitchen-1	6240	1790	8030
Gents Restrooms-2	2080	2559.1	4639.1
Ladies Restrooms-3	2080	2559.1	4639.1
Dining-4	8153.6	34803.8	42957.4
Dining-5	5657.6	18425.6	24083.2
Dining-6	5387.2	13307.4	18697.6
Bar-7	8257.6	30709.3	38966.9

7. Ventilation Flowrates

Based on the minimum recommended outdoor air flow rates in **Table A3**, the design outdoor airflow to provide necessary ventilation for each zone (**Table 7**).

Table 7. Required airflow rates.

Zone	Maximum Occupancy	Airflow rate per person (cfm)	Total airflow rate (cfm)
Kitchen-1	7	15	105
Gents Restrooms-2	10	20	200
Ladies Restrooms-3	10	20	200
Dining-4	136	20	2720
Dining-5	72	20	1440
Dining-6	52	20	1040
Bar-7	100	30	3000

7.1. Diffusers and Air Handling Unit Location

In ventilation, each element has a specific role, and their placement can significantly impact the performance of the entire system.

Diffusers are responsible for distributing conditioned air throughout a zone. The goal is to achieve uniform airflow, preventing drafts and maintaining a comfortable environment. The placement of diffusers should consider factors such as room size, layout, and occupancy. In larger spaces, several diffusers may be strategically located to ensure even coverage, while in smaller rooms, a well-placed diffuser can work wonders. AHU conditions and circulates the air. Ideally, AHUs should be located to optimize efficiency and minimize energy consumption. Placing AHUs centrally can often reduce ductwork lengths, minimizing pressure drops and energy losses. Additionally, considering access for maintenance and minimizing noise impact on occupied spaces are crucial factors in AHU placement [12].

The number of supply diffusers in each room are based on the required airflow and have been are distributed as shown below [13] (**Figure 3**).

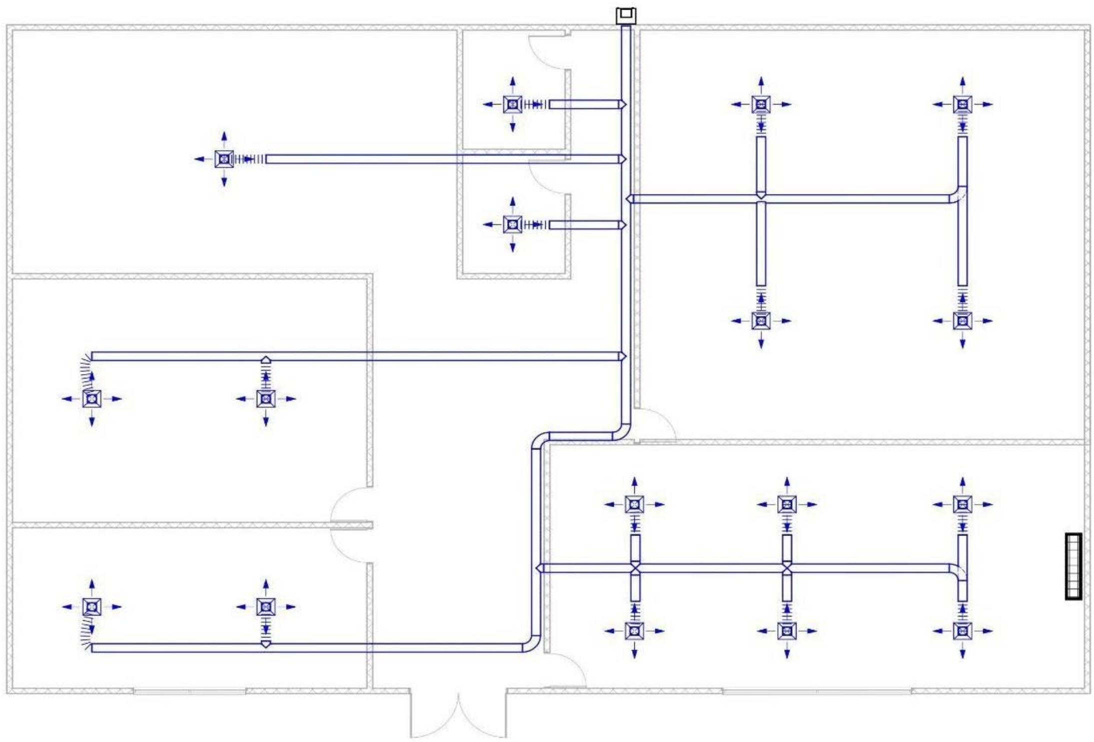


Figure 3. Number of supply diffusers.

7.2. Duct Layout

The systematic arrangement and design of ductwork within the building is shown in figure above (**Figure 4**). The goal is to efficiently and effectively distribute conditioned air throughout the building while maintaining comfort, energy efficiency, and adherence to safety standards [9].

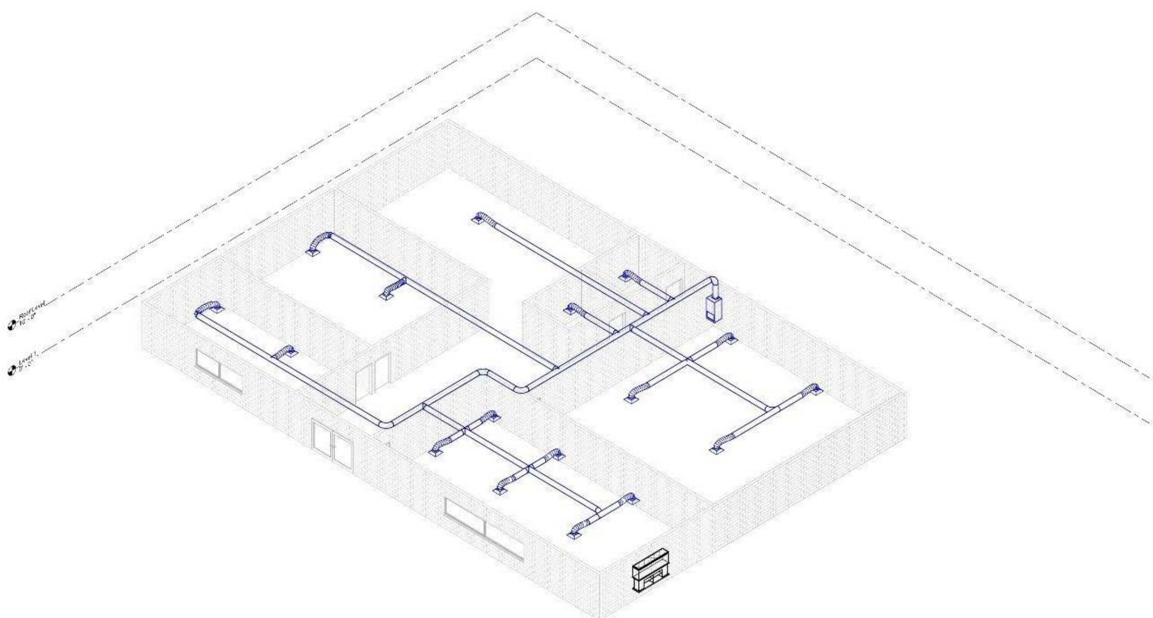


Figure 4. Ductwork design.

7.3. Duct Sizing

The design procedure for the equal friction method will be followed based on the following considerations and assumptions [14]:

- The duct system has been laid out with all of the supply branches (shown above).
- The properties will be assumed constant and the standard value of density (0.0765 lb/ft^3) will be used.

1) Determine Airflow Requirements:

Calculate the total airflow (CFM) needed for the HVAC system based on heating or cooling load calculations for each zone (**Table 8**). This step was done in phase II of the project and the following was obtained:

Table 8. Total Airflow rates (CFM) in each zone.

Zone	Maximum Occupancy	Airflow rate per person (cfm)	Total airflow rate (cfm)
Kitchen-1	7	15	105
Gents Restrooms-2	10	20	200
Ladies Restrooms-3	10	20	200
Dining-4	136	20	2720
Dining-5	72	20	1440
Dining-6	52	20	1040
Bar-7	100	30	3000

2) Select a Friction Rate:

Choose a friction rate per 100 feet of duct. The friction rate is typically expressed in inches of water column per 100 feet of duct (e.g., 0.08 inches/100 ft.). This rate helps maintain a consistent pressure drop throughout the duct system [15].

For each duct section, the diameter is determined by using the specified friction loss per unit length $(\Delta Lp)_f$, in this case, taken to be 0.001 in H_2O/ft and the required flow rates.

3) Determine Friction Loss:

Calculate the friction loss for the selected duct size using the chosen friction rate and the duct length using the following formula:

$$\Delta pfr = (\Delta Lp)_f \times L$$

A simplified schematic of the duct layout is as follows (**Figure 5**).

The loss coefficient for different fittings is given below (**Table 9**).

Table 9. Loss coefficient for various fittings.

Fitting	
Entrance	0.05 K^L
Bend	0.1

Continued

Wye, straight	0.13
Wye, turn	0.4
Diffuser	0.1

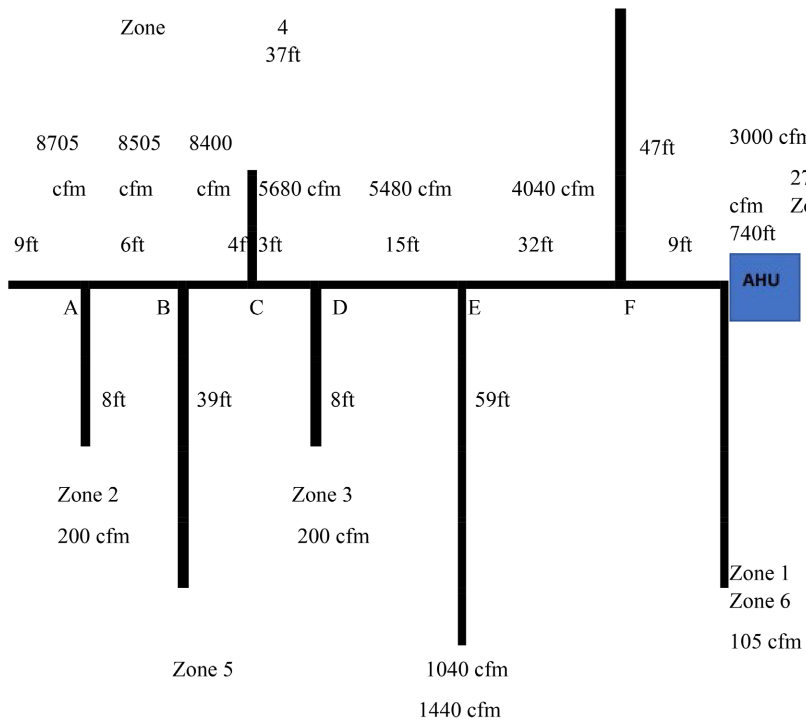


Figure 5. Duct layout.

The resulting duct diameters, velocity and total frictional pressure drop are given in the tables below [16] (**Table 10**).

Table 10. Approximate duct diameters for first duct line.

Section	Specified friction loss (in H_2O/ft)	Approximate Diameter (in)	Velocity (fpm)	Friction Pressure Drop (in H_2O)	K^L
AHU-A	0.001	31.5	1750	0.009	0.1
A-2	0.001	7.5	680	0.008	0.2
A-B	0.001	31	1700	0.006	0
B-1	0.001	5.8	550	0.039	0.1
B-C	0.001	30	1650	0.004	0
C-4	0.001	20	1280	0.037	0.5
C-D	0.001	26	1450	0.003	0
D-3	0.001	7.5	680	0.008	0.2
D-E	0.001	25.5	1250	0.015	0
E-5	0.001	14	1020	0.059	0.3

Continued

E-F	0.001	23	1400	0.032	0
F-7	0.001	20.5	1300	0.047	0.7
F-6	0.001	15	1010	0.040	0.3

4) Fittings pressure loss:

The pressure drops in each section associated with the fittings is given by:

$$p = \sum K \rho_2 V^2 \Delta \cdot KL$$

After obtaining the fitting pressure drop using the formula above, both frictional and fitting pressure drops are tabulated below for both lines (**Table 11**).

Table 11. Total Pressure drop.

Section	Friction Pressure Drop (Pa)	Fitting Pressure Drop (Pa)	Friction Pressure Drop (Pa)
AHU-A	2.24	4.74	6.98
A-2	1.99	1.43	3.42
A-B	1.49	0	1.49
B-1	9.71	0.46	10.17
B-C	1.00	0	1
C-4	9.22	12.68	21.9
C-D	0.75	0	0.75
D-3	1.99	1.43	3.42
D-E	3.74	0	3.74
E-5	14.70	4.83	19.53
E-F	7.97	0	7.97
F-7	11.71	18.31	13.02
F-6	9.96	4.73	14.69

8. Zone Pressures

Zone pressures play a crucial role in maintaining a balanced and efficient HVAC system. During the design, consider the desired pressure differentials between zones based on the intended use of each space [17]. Proper design ensures that the HVAC system effectively meets the specific needs of the building [18].

To determine the pressure in each zone, establish the total pressure of the supply fan based on the longest duct run:

$$L_{\text{longest}} = 9 + 6 + 4 + 3 + 15 + 32 + 49 = 118\, ft$$

The pressure at the exit of the AHU is then determined by adding the pressure drops along this run:

$$\text{PAHU} = 14.69 + 7.97 + 3.74 + 0.75 + 1 + 1.49 + 6.98 = 36.62\, Pa$$

The pressures in each zone can be based on this pressure and obtained (Table 12).

Table 12. Pressure in each zone.

Zone	Maximum Occupancy
Kitchen-1	17.98
Gents Restrooms-2	26.22
Ladies Restrooms-3	22.98
Dining-4	5.25
Dining-5	3.13
Dining-6	0
Bar-7	1.67

9. Conclusion

The process of designing a restaurant's heating and cooling system requires striking a careful balance between selecting components that are both economical and efficient and satisfying capacity demands for a range of situations. Keeping both initial prices and ongoing expenses in mind, the objective is to guarantee a cozy and healthful interior atmosphere [19]. A key factor in achieving balanced pressure drops and optimal energy efficiency in HVAC duct design is the equal friction approach, which is well-known for its effectiveness. It emphasizes the need for constant friction rates throughout the ductwork. In order to obtain the required friction rate, which promotes equal airflow distribution and system balance, engineers use a methodical procedure that takes into account aspects including total airflow needs, zoning, and iterative modifications to duct diameters. In order to maintain maximum performance, it is imperative to consider space limits, equipment compatibility, and constant system monitoring. This technique complies with industry requirements, guaranteeing reliability in the field. All things considered, the equal friction approach is a useful tool for creating HVAC duct systems for restaurants that are both balanced and effective.

Objective

- Sketch of the building in AutoCAD.
- Find design day weather conditions.
- Calculate air flow rate for each room.
- Calculate the design heating and cooling loads for each room.
- Calculate design cooling coil load.
- Determine the diffusers and grilles location within the space.
- Determine the AHU location within the building.
- Layout entire duct work.
- Size the ducts using equal friction method.
- Determine the total pressure requirements.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Design weather data for selected locations (English units).

a

Location	Lat deg	Long deg	Elev (ft)	Std pres. psia	Cold month	Heating DB (˚F) 0.986	Heating DB (˚F) 0.99	Heating Wind mph
Miami, FL	25.8	80.3	13	14.69	1	46.3	50.5	9.9
San Francisco, CA	37.6	122.4	16	14.69	1	37.8	40	5.4
Washington, DC	38.9	77	10	14.69	1	15.9	20.2	11
Madison, WI	43.1	89.3	860	14.25	1	−10.3	−4.8	7.8

b

Location	Hot month	Range ˚F	Cooling DB/WB (˚F) 0.004	Cooling DB/WB (˚F) 0.01	Cooling DB/WB (˚F) 0.02	Wind mph
Miami, FL	7	12	91.6/77.5	90.4/77.4	89.4/77.3	10.5
San Francisco, CA	9	16.1	83.0/62.9	78.0/62.0	74.1/60.9	13
Washington, DC	7	16.4	94.5/75.9	91.9/75.3	89.3/74.0	10.5
Madison, WI	7	21.1	90.0/73.7	87.0/72.2	84.2/70.7	11.7

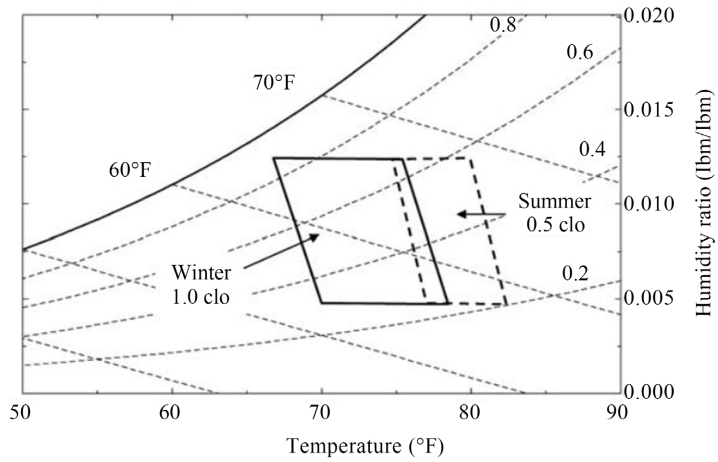

Figure A1. ASHRAE comfort regions for summer and winter (English units).

Table A2. Selected R-values of various building materials.

Element	R-value $\left(\frac{hr-ft^2-F}{\text{Btu}}\right)$	R-value $\left(\frac{m^2-C}{W}\right)$	Element	R-value $\left(\frac{hr-ft^2-F}{\text{Btu}}\right)$	R-value $\left(\frac{m^2-C}{W}\right)$
Structural elements			Windows		
Gypsum board $\left(3/8''\right)$	0.3	0.05	Single glazing	0.9	0.16

Continued

Shingles	0.4	0.07	Double glazing (metal frame)	1.6	0.28
Plywood $\left(\frac{1}{2}''\right)$	0.6	0.11	Double glazing (wood frame)	1.9	0.34
Siding	0.8	0.14	Double glazing, low emittance	2.5	0.44
Brick (4")	0.4	0.07	Triple glazing	2.2 - 3.6	0.34 - 0.63
Concrete	0.83/in.	0.058/cm			
Concrete block (8")	1.1 - 1.7	0.19 - 0.30			
Carpet and pad	2.0	0.35			
Insulation			Outside surfaces		
Loose fill	2.5/in.	0.17/cm	Winter	0.17	0.030
Batts	3.6/in.	0.25/cm	Summer	0.25	0.044
Closed-cell foam	5.0/in.	0.35/cm	Inside surfaces	0.68	0.12
Drapes	1.0	0.18	Horizontal air spaces		
			High emittance	1.2	0.21
			Low emittance	3.0	0.53

2009 ASHRAE Handbook of Fundamentals, Chapter 26.

Table A3. Minimum recommended outdoor air flow rates at design conditions.

Application	Function	Design occupancy (per 1000 ft^2 [100 m^2]	Minimum outdoor airflow rate per person (unless otherwise specified)	
Office building	Offices	7	20 cfm	10 L/s
	Conference rooms	50	20 cfm	10 L/s
Restaurants	Cocktail lounge	100	30 cfm	15 L/s
	Dining room	70	20 cfm	10 L/s
	Kitchen	20	15 cfm	7.5 L/s
Hotel	Bedrooms	-	30 cfm per room	15 L/s per room
	Conference rooms	50	20 cfm	10 L/s
Retail store	Shops, malls	20	0.2 cfm/ft^2	1 L/s m^2
Educational facility	Classrooms	50	15 cfm	7.5 L/s
Hospital	Patient rooms	10	25 cfm	12.5 L/s
Residence	Living areas	-	15 cfm	7.5 L/s
Sport area	Ballrooms	100	25 cfm	13 L/s
	Gymnasiums	30	20 cfm	10 L/s

ANSI/ASHRAE Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality (2010).

Table A4. A brief summary of the minimum reguirements from the ASHRAE Ventilation.

S/N	Activities	SHG (Watt)	LHG (Watt)
1	Seated at rest	60	40
2	Seated, very light work, writing	65	55
3	Seated, eating	75	95
4	Seated, light work, typing	75	75
5	Standing, light work, walking, slowly	90	95
6	Light bench work	100	130
7	Light machine work	100	205
8	Heavy work	165	305
9	Moderate dancing	120	255
10	Athletics	185	340

Source: ASHRAE, 2011.

Since the space temperature is not maintained constant during the 24 hours period, then the Cooling Load Factor (CLF) is 1.

b. Electric Lights: The equation to calculate the cooling load due to Electric lights is given as in (5):

$$Q_{\text{sensible}} = 3.41i \times W \times \text{FUT} \times \text{FBF} \times (\text{CLF}) \tag{5}$$

W = Installed lamp watts input from electrical lighting plan or lighting load data.

FUT = Lighting utilization factor.

FBF = Blast factor allowance, as appropriate.

CLF = Cooling Load Factor, by hour of occupancy. For this research, the Cooling Load Factor is 1.

The Wattage is determined by looking at the current rating of the lamp and multiplying that with the standard voltage (240 V). The Light Utilization factor (FUT) is calculated as the ratio of the light current in use to the total number of light presently installed. The Blast factor allowance (FBF) is 1 for compact fluorescent Light (CFL) and 1.2 for ordinary fluorescent tube.

c. Appliances: The equation to calculate the cooling load due to appliances is given as in (6):

$$Q_{\text{sensible}} = 3.41 \times W \times F_u \times F_r \times (\text{CLF}) \tag{6}$$

W = Installed rating of appliances in watts according to the manufacturer's data.

F_u = Usage factor.

F_r = Radiation factor.

CLF = Cooling Load Factor, by hour of occupancy.

For the sake of this research work, the Cooling load factor for heavy equipment is taken as 0.16 while for light equipment is taken as 0.12 (ASHRAE.2011).