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A Course on Air Quality Monitoring and Control for Mechanical Engineering Seniors

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The author has an adjunct faculty appointment at the Mechanical Engineering Department of the University of St. Thomas (MN), where he has been involved in the development and instruction of laboratory courses in fluid mechanics, thermodynamics, and heat transfer. He has a long-standing interest in air quality management and control. This course is a part of a package of electives including a course on water quality management and control offered by the Civil Engineering Department.

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Abstract

This course was intended for professional preparation of students interested in air quality monitoring and control roles in the public or private sector, as well as advanced HVAC engineering roles covering indoor air pollution management in addition to temperature and humidity control. The course began with learning/reviewing the principles of fluid mechanics and thermodynamics relevant to indoor and outdoor air quality. Concerning outdoor air quality, the course content included introduction to key air pollutants, EPA standards for air quality, rationale behind the standards, air quality index (AQI) calculation, and sources of pollution. The use of equilibrium thermodynamics in predicting air quality was introduced and resources available for equilibrium calculation were identified. The relevant sensor technologies were also introduced. Concerning indoor air quality, the course content covered air-conditioning basics for temperature and humidity control, which was supplemented with the strategies for monitoring and controlling pollutants using air filtration, ventilation and air purification. Filter standards and filter testing technologies were discussed. ASHRAE and OSHA guidance concerning healthy indoor air quality (IAQ) was covered. A low-cost air quality sensor was installed in the classroom that streamed data to the internet. Students were assigned projects utilizing this sensor and the neighboring outdoor sensors, which triggered interest in citizen science.

1. Introduction

Air quality has been a subject of college education in engineering for many years, often included in environmental engineering programs, which are frequently integrated with civil engineering. Civil and environmental engineering departments exist at leading institutions such as Berkeley (https://ce.berkeley.edu/), Stanford (https://cee.stanford.edu/) and Northwestern (https://www.mccormick.northwestern.edu/civil-environmental/). Also, air quality education is found to align well with chemistry and chemical engineering education, as monitoring pollutants involves detection and quantification of certain chemicals. A textbook on air quality from a chemical engineering perspective has been available for many years (*1*). Air quality content in chemistry textbooks for liberal arts undergraduates was recently used in an investigation of evidence for curricular relevancy from a public policy point of view (*2*). Air quality education for mechanical engineering undergraduates is considered here. This paper reports on the outcome of the first offering of an air quality monitoring and control course for mechanical engineering seniors. The specific aim of this course was professional preparation for three types of future roles for the students:

1. air quality engineering roles at the regulatory agencies,
2. air quality engineering roles at the industries that are required to meet the air quality regulations,

3. HVAC engineering roles covering indoor air pollution management in addition to temperature and humidity control.

It was a 2-credit course, and students needed to take another 2-credit course to earn the credit for one elective. A ‘natural companion’ to this course was a 2-credit course on water quality. Ten out of eighty students in the graduating class were interested in this track. However, due to inconvenient scheduling (air quality course being offered MWF morning for ½ semester; water quality course being offered Thursday afternoon for full semester) only four students attended this course. The school of engineering plans to offer the air/water quality course as a package in Spring 2026 again and expects 10-15% participation from the seniors.

The professional preparation goals for this first offering were diverse. Based on the student feedback, we would be narrowing it down to professional preparation for advanced HVAC engineering only.

2. Fluid Mechanics of Air Quality

Students in this course were familiar with the basic principles of fluid mechanics and were challenged with applying them to the dynamics of solid and liquid particles in gases. Corrections to classical fluid mechanics correlations were introduced for the cases when the ratio of particle size to the mean-free-path of the surrounding molecules is small. Particle removal/deposition mechanisms (sieving, sedimentation, inertial impaction, and diffusion) were taught and applied to air filters and human lungs.

In one of the assignments, students collected particle concentration data in a classroom using PurpleAir Touch™ Indoor Air Quality Monitor and found a negative correlation between PM2.5 concentrations and the room occupancy confirming the effectiveness of fine particle deposition in human lungs (the term fine particle in the present context refers to particles smaller than 2.5 microns in aerodynamic diameter (*3*)). The correlation was however weak and further investigation was suggested, possibly in spaces with large variations in occupancy.

In another assignment, students were given the physical dimensions and inhalation flow rate of an average human lung and tasked with tracking particles of different aerodynamic diameters, ranging from 1 nm to 10 microns. Using the formulas for particle deposition by sedimentation, inertial impaction and diffusion, students were able to recognize that only fine particles would reach the acinar airways where they might deposit in the alveoli.

In the application of particle removal/deposition mechanisms to filters, it was emphasized that the highest penetration (or lowest filtration efficiency) occurred at an intermediate particle size, which was large enough to avoid loss by diffusion but small enough to evade loss by impaction or sedimentation. A guest speaker with expertise in filtration technology explained the importance of transit time through the filter, air face velocity and pleating of the filter. Students were made familiar with MERC and HEPA ratings of the filters.

3. Thermodynamics of Air Quality

Fluid mechanics teaches that fine particles have a high likelihood of depositing in alveoli and pose challenges in removal by filtration. Thus, the chemical composition of these particles is of interest, as chemically reactive particles, especially oxidative agents, are more harmful to health than chemically less reactive coarse particles originating from dust, volcanic ash and sea spray. Fine particles are mostly synthesized out of gas phase and their concentration depends on the concentration of their gaseous precursors, as well as temperature and humidity. This is a topic in equilibrium thermodynamics (*4*).

Students in this course were familiar with the principles of thermodynamics as applied to power generation and refrigeration. It was emphasized that modern thermodynamics has gone beyond conversion of heat into mechanical work and vice versa. Whereas classical thermodynamic processes are constrained by the tendency of simple substances to approach thermal and mechanical equilibria, reacting substances have the additional constraint of the tendency of approaching a chemical equilibrium. Gibbs function was introduced as the property that determines the equilibrium composition of a reacting mixture. Students were introduced to E-AIM Aerosol Thermodynamics Model (Model IV: Comprehensive Calculations) for calculating liquid and solid phase fine particle concentrations starting from ionic concentrations of pollutants (sulfate, nitrate, ammonium, etc.) released into the atmosphere (*5*). They were asked to estimate aerosol concentrations under different atmospheric temperatures and humidity for a certain set of ionic pollutant concentrations. This helped them appreciate that a certain source of pollution can be more harmful under a given atmospheric condition than the other. High humidity increases the risk of pollutants depositing in people's lungs.

4. Epidemiology and Regulations

The harmful health effects of fine particles are predicted by the fluid mechanics and thermodynamics of pollutants. There is also direct evidence that mortality is associated with air pollution that occurs in the form of fine particles. In this context, 'Six Cities Study' (*6*) has an important place in scientific literature on air pollution. Students were required to engage in a close reading and classroom discussion of this epidemiological study. This was an exercise in learning from a research paper outside of engineering disciplines. Students felt comfortable in using context clues in understanding the meaning of unfamiliar terms with the instructor's assistance.

Next, we engaged in a discussion of the Clean Air Act and EPA regulations, covering both particulate and gaseous pollutants. In a classroom exercise, students determined that permissible emission limits for gaseous pollutants (ozone, carbon monoxide, SO_2, NO_2, etc.) are at least one order of magnitude higher than the permissible limit for fine particles. This is expected from the knowledge of deposition mechanisms learnt in the section on Fluid Mechanics of Air Quality. Students learnt to calculate Air Quality Index (AQI) manually and using online resources. They accessed nearby EPA sensors on www.airnow.gov and understood the meaning of NowCast AQI.

Management of outdoor air quality requires regulation of the sources of pollution. These are broadly divided into mobile and stationary sources. Discussion of these topics was brief. Sensor technologies for monitoring stationary sources were explored in one of the assignments.

5. Discussion of Citizen Science

Use of low-cost sensor networks has recently been reported for citizen science projects (*7*, *8*). In one of the assignments, students sought correlations between the measurements taken by an indoor PurpleAir sensor versus a nearby outdoor PurpleAir sensor. The locations of the sensors are shown on a map in Figure 1. Pearson correlation coefficient between indoor and outdoor AQI was 0.99 for a 24-hr period (1 p.m. Day 1 to 1 p.m. Day 2). Indoor AQI exceeded outdoor

AQI—especially on Day 2, which was traced back to the construction activity just outside the building where indoor sensor was located. Since the outdoor sensor was located 0.5 mile away from the construction site, it measured much lower AQI as the pollutants (mostly fine particles) diffused away from the source. This started a discussion on how citizens could be taught to utilize low-cost sensor networks to monitor various sources of pollution in their neighborhoods. Later, in assessments, students indicated an interest in leading citizen science projects.

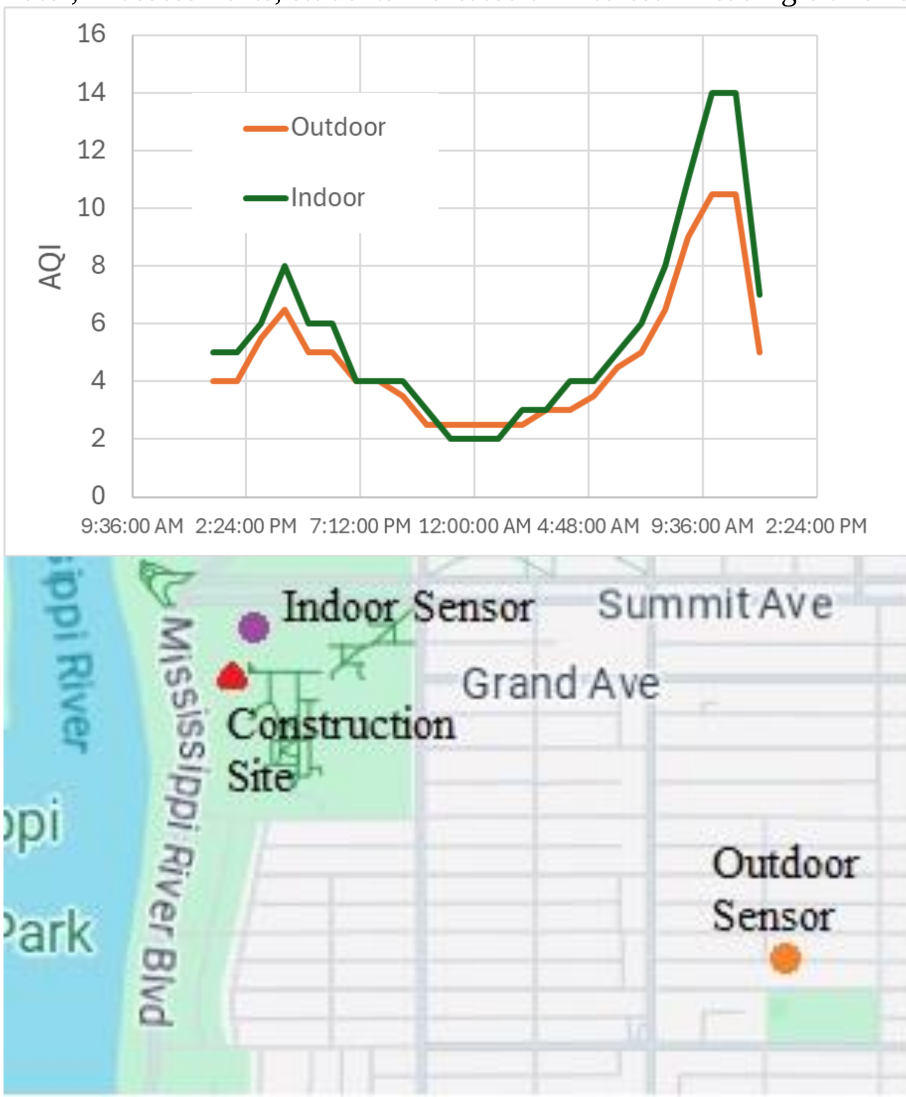

Figure 1: Indoor versus outdoor AQI and locations of the sensors and the construction site

6. Indoor Air Quality

Indoor air quality (IAQ) is affected by the outdoor air quality as well as indoor sources of pollution. OHSA and ASHRAE Standards for IAQ were reviewed. The discussion covered well-known contaminants such as carbon monoxide, carbon dioxide and radon as well as less known air pollutants such as pesticides, legionella, and volatile organic compounds (VOC). The general message has been that prevention is better than cure. EPA's program of Indoor airPlus Homes was introduced and discussed. Pros and cons of the emerging air cleaning technologies, such as ionizers, electrostatic precipitators and UV germicidal irradiators were discussed. Students were challenged to validate the product specifications of commercial air cleaners. It was found that commercial suppliers often claim to cover 4-5 times the floor area than their products are proven to cover in EPA sponsored studies.

7. HVAC: Principles and Practices

Students in this course were familiar with the principles of refrigeration and had an introduction to psychrometric chart. Classroom exercises helped students represent common air conditioning processes on the psychrometric chart. These included cooling, heating, evaporative cooling, cooling with dehumidification. Industry practices in load design calculations were introduced. A guest speaker from HVAC-industry discussed current trends in system design such as reduction in pressure drops in the ducts to reduce fan power, as well as heat recovery means. Current trends in building automation and the future role of AI were discussed. Whereas leading HVAC suppliers such as Trane offer air purification technologies, a holistic approach has not yet emerged to seamlessly combine air quality control measures with the conventional goals of HVAC design. Students were made aware that the current practices in HVAC design may not be in sync with the need for the best air quality. It may be necessary to maintain a lower humidity than conventionally perceived to be comfortable, to suppress biological contaminants. Likewise, higher than conventional ventilation may be desirable to dilute the pollutants from the indoor sources.

8. Assessments and Feedback

The assessments were based on a last-day survey versus first-day survey (Appendix). In these surveys students identified their primary goals as learning about air quality terminology, AQI calculations, indoor air pollution control and HVAC basics. There was a high level of interest in advanced HVAC engineering roles covering air pollution abatement in addition to temperature and humidity control. There was somewhat less interest in air quality engineering roles at the regulatory agencies or in the industries that are required to meet the regulatory requirements. At the beginning of the course, students had anticipated challenges in keeping up with the pace of the course due to a perceived lack of background. They reported meeting this challenge at an average level of 7.5 on a 1-10 scale. The required backgrounds in mathematics and chemistry were matters of concern at the beginning of the course, but in the end, mathematics was found to be non-challenging. Pearson correlation coefficient was new to the students, but they quickly learnt how to use the pertinent Excel function.

The comfort level in learning from published scientific material from a non-engineering discipline was also assessed. After reading an epidemiology study concerning the correlation between fine particle pollution and mortality, some students reported an increase in comfort level in deciphering non-engineering scientific material. Students reported no prior involvement in citizen science at the beginning of the course but indicated at the end that they are somewhat likely to participate in a citizen science project if an opportunity arises.

Accomplishment in dealing with environmental chemistry was assessed to be 5 on a 1-10 scale by one of the students. This may be irrelevant as we are considering removal of the environmental chemistry section to free up time for additional discussion of HVAC.

9. Andragogical Approach

Malcolm Knowles's assumptions of motivation for adult learners were found to be relevant and valuable for structuring this course (*9*). Unlike children, adults need to know the reason for learning, they respond to internal versus external motivators, and are most interested in learning things of immediate relevance. They are problem-centered, bring their own experience to the classroom and are responsible for their own education. It is understood that there may be some exceptions to these broad assumptions, but they provided valuable guidelines for structuring the course. Twenty-five percent of the course grade was assigned to a team project on an air quality topic chosen by the students. Speakers from the industry were invited to share their experiences and highlight the relevance of the course content to engineering practices and problem solving. Fifty percent of the course grade was assigned to four major assignments involving investigation of real-world problems. As an example, as elaborated in Sec. 2 above, students investigated penetration of particles of various aerodynamic sizes into a typical human lung using the principles of aerodynamics. The remaining twenty-five percent of the grade was determined by small assignments, in-class worksheets and participation in the group activities. There were no formal examinations.

10. Conclusions

Key elements of a 2-credit course on air quality management and control for mechanical engineering students are elaborated. This first offering of the course was aimed at professional preparation of the engineers for diverse roles in air quality engineering. Based on student feedback, the future offering should focus on professional preparation for advanced HVAC engineering roles, so the participants will be well-equipped to address the need for healthy air quality in addition to temperature and humidity control in conditioned spaces.

The advanced skills needed for air quality management and control are an extension of the basic knowledge of fluid mechanics, thermodynamics and heat transfer. These topics will be refreshed using the FE preparation material in future. Knowledge topics 10 (Fluid Mechanics), 11 (Thermodynamics), 12 (Heat Transfer) and 13 (Measurements, Instrumentation, and Controls) of FE Exam Specifications (*10*) will be covered. Specific emphasis will be placed on

- (i) Power, efficiency and scaling laws for fans and pumps (Topic 10G-I)
- (ii) Refrigeration, Psychrometrics, and HVAC (Topic 11G-J)
- (iii) Heat exchangers (Topic 12E)
- (iv) Measurement uncertainty (Topic 13D).

This course will be packaged with another 2-credit course on water quality, so the combination of these courses will enable students to earn the credit for an elective.

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Appendix
Assessment: Questionnaires and Responses

1. What is the most important thing you hope to learn, or get out of this class?

First Day Response	Last Day assessment on a scale of 1-10
Basic knowledge of air quality control and HVAC systems	9
How to deal with air pollutants?	8
Better understand the air quality terminology; how it is determined?	7
Calculating AQI	8

2. Second most important thing?

First Day Response	Last Day assessment on a scale of 1-10
Outdoor air quality control	7
The hazards of air pollutants; where they come from? how they are created?	10
To understand different pollutants and their differing effects	8
Learning more about HVAC systems	10

3. What challenges do you anticipate in this course?

First Day Response	Last Day assessment on a scale of 1-10
The math involved may be a little complex	10
Understanding chemistry in this course	5
Lack of any considerable background in the topic	8
Completing assignments on time	7

4. On a scale of 1-10, how well do you learn by merely reading an engineering textbook without instructor assistance?

First Day Response	Last Day Assessment
7	8
6	7
9	9
6	8

5. On a scale of 1-10, how well do you learn by merely reading engineering papers and reports not written on a textbook format?

First Day Response	Last Day Assessment
7	8
4	6
7	7
7	9

6. On a scale of 1-10, what is your level of comfort with reading journal papers in a scientific discipline outside of engineering? (1: never done it, not sure how it would go, 10: have done it many times, it is not a big deal)

First Day Response	Last Day Assessment
9	10
1	5
6	8
10	10

7. First Day: Have you ever been involved in Community Science to address environmental issues? Last Day: If an opportunity arises how likely are you to participate?

First Day Response	Last Day Response
No	Somewhat likely
No	Somewhat likely
No, but that sounds interesting	Somewhat likely, I would be interested in providing data towards research in a study like 6 cities
No	Somewhat likely

Notes:

1. Student responses were blinded to the peers but not to the instructor.
2. After the last-day survey, there were informal follow-up conversations between the instructor and the individual students. All the students expressed interest in learning more about HVAC and indoor air quality maintenance.