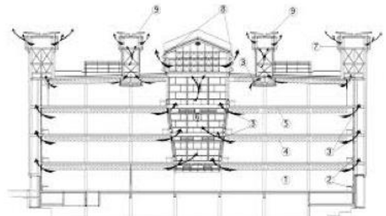
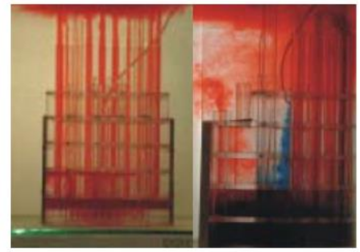
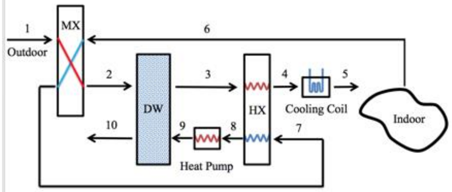
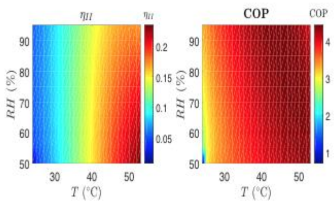
Space-Conditioning Systems for Low-Carbon Buildings
4.421 Department of Architecture Spring 2022



Images: UCL, BPI Cambridge, MIT and NUS

Instructor: Les Norford lnorford@mit.edu Teaching Assistant: Ramon Weber reweber@mit.edu
Lectures Monday and Wednesday, 2:00-3:30, Room 5-415; Lab Monday 3:30-5, Room 5-415;
In-person teaching; lectures will be Zoom-recorded as needed for academic continuity
Units: 3-2-7; 3-2-4 available. Class is open to students in all degree programs

Consensus understanding of climate change identifies a need to drastically reduce anthropogenic emissions of greenhouse gases in coming decades, including those associated with buildings. In this course, we seek a thermofluids understanding of the basics of natural and mechanical systems for conditioning high-performance buildings and will develop and assess systems based on this understanding. We will consider options for new and existing buildings. Can these and other buildings, large or small, meet municipal and global goals for decarbonization? Should they simply depend on a decarbonized grid or can energy consumption be substantially reduced relative to current practice? Can they be maintained at a comfortable temperature with little or no use of mechanical systems? Can waste heat at building or community scale be effectively captured and reused?

We will investigate natural ventilation in detail, including the thermal and fluid dynamics of airflow in buildings,application to multi-zone wind- and buoyancy-driven airflows, and adjustments in urban areas to account for reduced wind speeds. Performance assessments will be based on first-principles analyses and simulations that couple airflow and energy analysis programs. Building cooling strategies will be motivated by mapping conventional and innovative cooling systems on the psychrometric chart. First-principles analysis and simulations with an equation-based language, Modelica, and with EnergyPlus will be used to quantify the performance of energy-recovery systems, membrane- and desiccant-based dehumidification, evaporative cooling, thermal storage at diurnal (building materials) and annual (ground-coupled heat pumps) scales and radiant cooling and heat-rejection systems. System design at building and district scale in leading commercial practice will be presented and critiqued. Working in groups and making use of design workflows under development at MIT and Harvard, we will assess climate- and building-specific systems on the basis of thermal comfort, energy consumption, carbon emissions and resilience to climate change.

Learning objectives

The objectives of the course are to help students:

- Understand the societal and environmental context of building energy consumption;
- Understand and apply the scientific principles underlying the thermal and fluid dynamic characteristics of buildings and building conditioning systems, and apply these fundamentals to practical design problems;
- Recognize design opportunities to use natural ventilation;
- Develop an ability to use contemporary component and whole-building simulation programs to analyze building performance;
- Learn to evaluate a range of technologies for creating comfortable indoor environments and
- Demonstrate an ability to critically discuss and present the environmental concept of low-energy and low-carbon building systems integrated into a building.

Requirements

This course requires the following:

- Attendance of bi-weekly lectures;
- Timely completion of assignments that involve analytic and computational assessment of system performance;
- Completion of a group course project;
- Active participation in class discussions.

Course grading

60% homework assignments (all but the first in teams of 2-3)
10% project proposal
20% project presentation
10% class participation

Please familiarize yourself with MIT's Academic Integrity Expectations at http://web.mit.edu/academicintegrity/. We will largely work in groups; information shared from other groups should be acknowledged.

Assistance with writing

The MIT Writing and Communications Center (WCC) offers free professional advice. Appointments may be made at https://mit.mywconline.com.

Required text

None. Readings will be assigned from multiple sources.

Office hours

Weekly office hours will be set to accommodate all schedules.

Software (we'll use many but not all of following programs, some of which)

- **Rhino 7** (https://www.rhino3d.com/download) is the 3D modeler we will use to represent buildings in a form that can be linked to performance analysis tools through the Grasshopper visual scripting program, which comes with the Rhino download.
- **Ladybug and Honeybee** (https://www.ladybug.tools) are two of the four insects developed by MIT Department of Architecture alumnus Chris Mackey (M.Arch and SMBT 2015) for building performance analysis in Grasshoppper. Ladybug can perform user-defined climate analyses, such as 3-D plots of temperature as a function of date and time and wind roses limited to specific outdoor temperatures. Honeybee links to EnergyPlus for energy analysis and to Radiance and Daysim for daylighting analysis, OpenStudio for HVAC system templates for EnergyPlus and THERM for thermal analysis of walls and windows. The installation instructions with the download provides the necessary URLs.
- **Dragonfly** (https://www.ladybug.tools) provides a means to estimate energy consumption at neighborhood scale by accessing NREL's URBANopt and the impact of urban development on the urban climate. It uses a Python-based version of the Urban Weather Generator developed at MIT.
- **Butterfly** (https://www.ladybug.tools), another Ladybug Tools insect! Butterfly links to a Windows-based version of OpenFOAM, for CFD analyses. Windows only.
- **Climate Studio** (https://www.solemma.com/climatestudio version 1.4 is the latest. https://www.climatestudiodocs.com/Installers/download.php?software=cs&version=networked) is a comprehensive climate analysis, daylighting and energy analysis package that runs under Rhino or Grasshopper. Windows only.
- EnergyPlus (https://energyplus.net) is the whole-building energy simulation program we will use to generate heating and cooling loads that must be met by space-conditioning equipment we will define and represent by seasonal efficiency metrics.
- **CC WorldWeatherGen** (http://www.energy.soton.ac.uk/ccworldweathergen/) morphs weather files to account for projected regional climate change.
- **CBE Thermal Comfort Tool** (http://comfort.cbe.berkeley.edu) is an interactive psychrometric chart developed by the Center for the Built Environment at UC Berkeley that will conditions that are acceptable thermal acceptable to humans.
- **CBE Clima Tool** (https://clima.cbe.berkeley.edu) is an online climate analysis and thermal comfort tool.
- **Psycho about Psychro** (http://www.comfortch.art), developed at Princeton University, encourages thinking outside the comfort box.
- **Climate Consultant** (http://www.energy-design-tools.aud.ucla.edu) is a freely downloadable tool that runs under Windows or Mac OS and provides a relatively comprehensive set of graphical presentations of data from standard weather files. We prefer Climate Studio and Ladybug Tools and the CBE and Princeton thermal comfort tools but acknowledge that Climate Consultant is easy to use for standard climate information.
- **Dymola** is an interface for the Modelica equation-based system analysis program. Download and installation instructions have been established by the SA+P IT service, STOA,

and will be provided at the appropriate time. We will use this to analyze advanced systems for cooling and drying air brought into buildings. Windows only.

- **CoolVent** (http://coolvent.mit.edu) is a freely downloadable tool developed at MIT for analyzing airflows and indoor temperatures associated with naturally ventilated buildings. Windows only.

Schedule as of 20220130

W1	1/31	L1	Climate change, urban heat island, buildings
		Lab	personal carbon budget, national and global carbon emissions, with attention to HVAC
		A1	National and personal carbon budgets (due 2/9)
		L2	Economics of building electrification
W2	2/7	L3	Low-energy building standards, practices and examples: Passive House, LEED, Living Building Challenge, etc.; energy and carbon emissions
		Lab	Exploration of carbon emissions data; Passive House in practice: Deborah Moelis, Handel Associates, NYC (previously recorded)
	2/9	L4	Indoor and outdoor thermal comfort. Implications for design, including air movement and cooling at the skin.
W3	2/14	L5	Natural ventilation toolkit
		Lab	Thermal comfort metrics and calculations; comfort-based control of MIT classrooms – Yuan Cai (MIT)
	2/16	L6	Buoyancy- and wind-driven airflow; two-way airflows through single openings; steady-state mass and energy balances
		A2	Multizone airflow calculations and application to solar chimneys (due 2/28)
W4	2/21	L7	Mass and energy balances for multiple zones in series, for wind and buoyancy flows; advanced analytic flows
		Lab	EnergyPlus via grasshopper and EP-Launch; LB intro – Sunghwan Lim (GSD)
	2/23	L8	Buoyancy-induced cooling
W5	2/28	L9	Building thermal dynamics, including night flush; African termite mounds; CoolVent for multizone flow and temperature calculations, with emphasis on chimneys
		Lab	Analytic solutions for mass and energy balances; exploration of the Torrent Research Center in Ahmedabad, India and the UCL School of East European and Slavic Studies (SSESS)
		A3	Buoyancy-induced cooling (due 3/14)
	3/2	L10	Moist-air processes, static and interactive psychrometric chart: condition line, mixing, sensible load factor; vapor compression system, direct and indirect evaporative cooling, argument for splitting sensible and latent

			heat removal: eliminated reheat, warmer water, opportunities for free sensible cooling, including radiation
	3/4		Add date
W6	3/7	L11	Introduction to Modelica – Dave Blum (LBNL)
		Lab	Modeling with Modelica
	3/9	L12	heat pump fundamentals, including refrigerants and their environmental impact
W7	3/14	L13	Heat pump part-load models, including DOE, Gordon-Ng and Zakula; efficiency metrics (EER, COP, IPLV). Low-lift options
		Lab	project development
		P1	Project proposal (due 3/28)
	3/14	L14	Ground-coupled heat pumps, sizing and performance Ground heat storage, passive and active; earth tubes; assessment of benefits of diurnal and seasonal energy storage
	3/21-25		Spring break!
W8	3/28	L15	All-air system (VAV), DOAS, heat and enthalpy recovery; membranes and desiccants for dehumidification; desiccant wheels and desiccant regeneration psychrometric chart calculations and visualizations
		Lab	Modelica modeling of vacuum membrane dehumidification
		A4	Modelica modeling of vacuum membrane dehumidification (due 4/6)
	3/30	L16	Water use for cooling and production of electricity: direct and indirect evaporative cooling and Maitsosenko dew-point indirect evaporative cooler; desiccant or membrane front ends; absorption and adsorption cooling
W9	4/4	L17	Liquid desiccant cooling
		Lab	Grand cooling challenge: what would you propose? – Ross Bronner (Transaera) and dry screen dehumidification Forrest Meggers (Princeton)
		A5	Passive chilled beam + ground heat exchange
	4/6	L18	Radiant cooling systems; active and passive chilled beams, thermally activated building slabs (TABS)
W10	4/11	L19	District heating and cooling systems. Stanford vs. MIT: heat recovery, co- and tri-generation
		Lab	Tour of MIT Central Utility Plant – Ken Ohlund or Mehdi Megherbi
		A6	Modelica modeling of district heating and cooling system (due 4/26)
	4/13	L20	Modelica modeling of district heating and cooling system; waste heat recovery at neighborhood scale
W11	4/18		Patriots Day holiday

	4/20		working session: Modelica modeling of DHC and/or project time
W12	4/26	L21	Radiant heat rejection (Stanford, UC Boulder, PNNL)
		Lab	project time
	4/28	L22	Optimization of structural and thermal systems – Edu Gascon and Manideep Rebbagondla
W13	5/2	L23	Sustainable HVAC systems in practice: Jacob Knowles, Director of Sustainable Design, BR+A Consulting Engineers (recorded)
		Lab	Optimization of temperature set points for heat resilience – Stella Zhang (MIT) (tentative); project time
	5/4	L25	hydrogen economy, fuel cells
W14	5/9		preparation for project presentations
		P2	project presentations
	5/10		Last day of classes