Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

- Chapter 1: testing methodologies and performance rating standards for heat pump systems -

Presenter: Niccolo` Giannetti

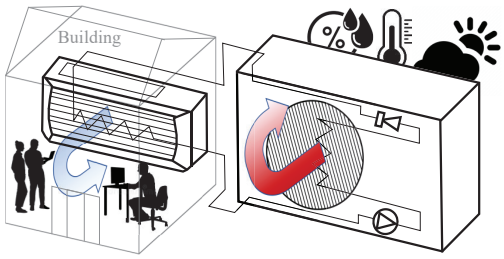
Chair: Takao Sawachi, Dr. Eng.
Operating Agent, IEA EBC Annex 88
IEA EBC Executive Committee Member
President, Building Research Institute, Japan
Chair, Committee on Evaluation Methods for Japan Building Energy Conservation Standard

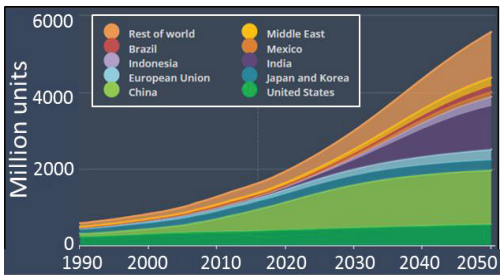
IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

Contents

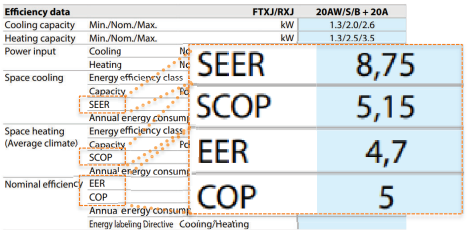
Technology Collaboration Programme
by iea

1. Background and Motivation





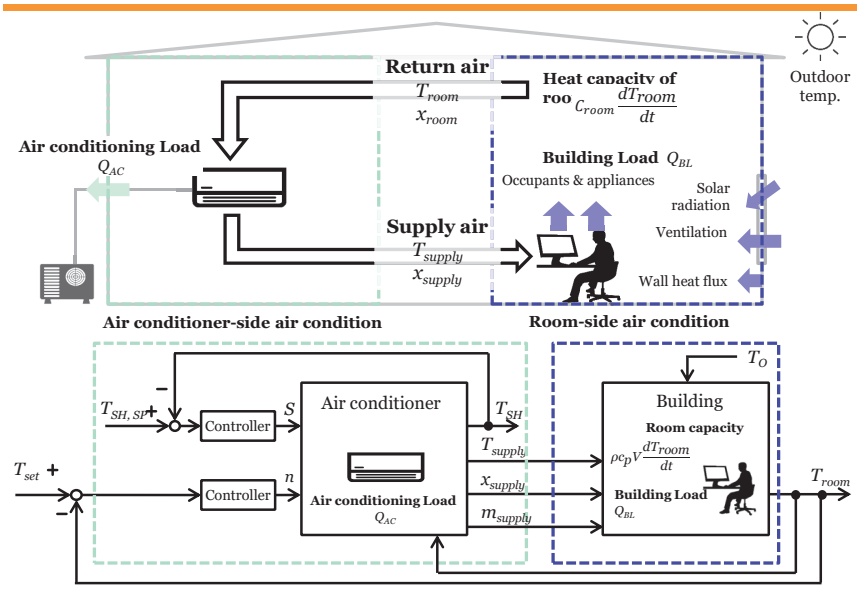
- Billions of heat pump installations interacting with building structures, occupants' lifestyles, and climates.
- Hardware performance
- Operation performance



- Operation performance and field performance of HP and AC installations remains largely unknown.

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
ANNEX 88 EBC Energy in Buildings and Communities Programme

1. Background – Field System Operation

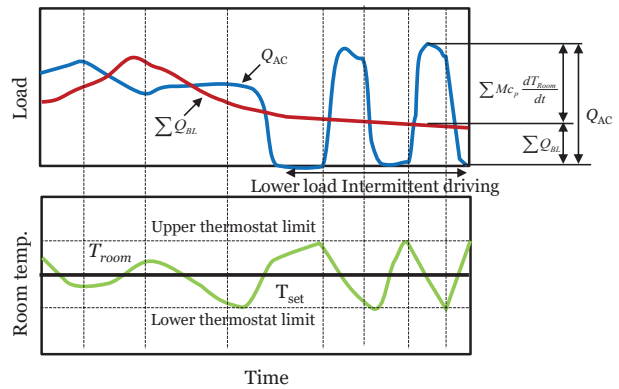


Block diagram of air conditioning control

- System operation

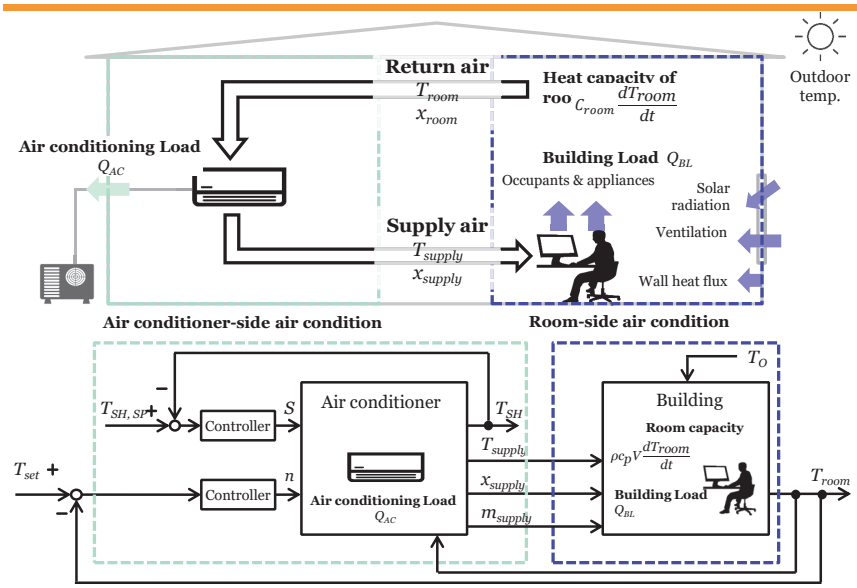
$$0 = \sum Q_{BL} - Q_{AC}$$

$$\sum Mc_p \frac{dT_{Room}}{dt} = \sum Q_{BL} - Q_{AC} \rightarrow \frac{dT_{room}}{dt} = \frac{\sum Q_{BL} - Q_{AC}}{\sum Mc_p}$$



* The estimation of moisture content and moisture transfer is also implied

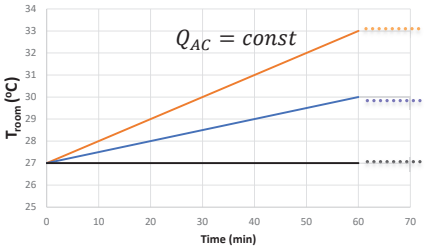
1. Background – Field System Operation



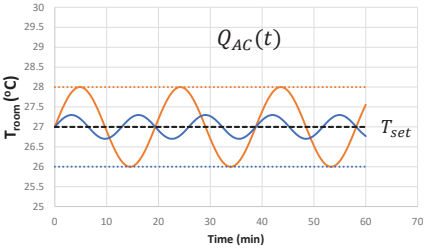
Block diagram of air conditioning control

❖ Deactivated-control operation

$$\frac{dT_{room}}{dt}=\frac{\sum Q_{BL}-Q_{AC}}{\sum Mc_p}$$



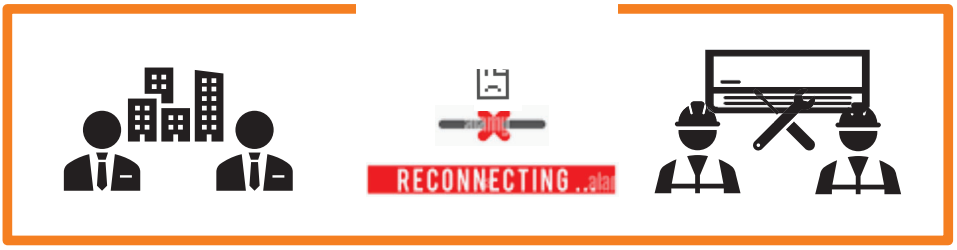
❖ Active-control operation



1. Background – Target Issue

❖ HPs performance depends on internal control, external parameters, and interactions with building features.

❖ Inconsistent viewpoints and technical approaches between HP designers, building owners and manufacturers .



Inappropriate design, control, sizing, and installation of heat pumps within buildings.

Gap between product and building performance

❖ Limited the potential of the heat pump technology as an integrated part of efficient buildings.

1. Background - Scope of the Project

Scope of the Project

- Provide shared viewpoints and transparent technological information transfer on heat pumps between technical experts, building owners and policymakers

Testing procedures	Energy calculation in buildings	Design and commissioning guidelines	Field performance monitoring

1. Review presently adopted testing methodologies and performance rating standards for air conditioners and heat pumps (Category A standards);
2. Review new testing procedures able to assess the performance of HPs and ACs when operated under the same control as operated in buildings (Category B standards);
3. Consider use of results to drive effective system design and control to maximize operational performance in buildings

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

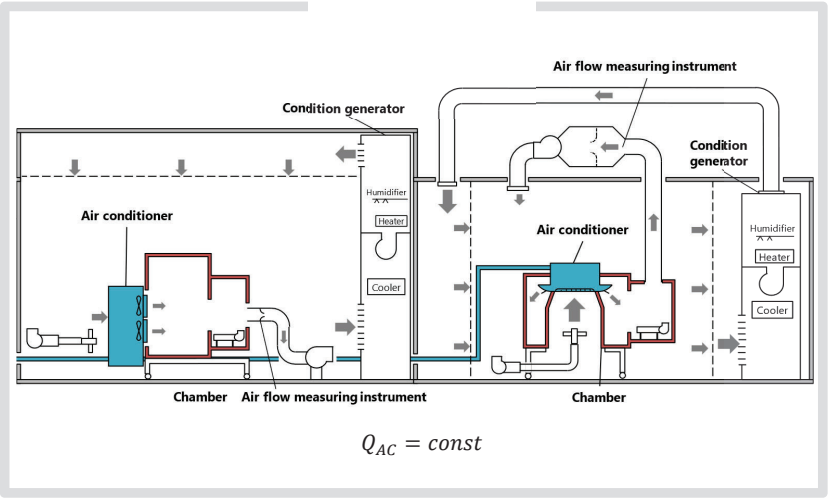
2. Categories of Testing Standards

	Category A standards:	Category B standards:
Operation mode during tests	❖ Proprietary control to forcibly impose steady-state condition during tests. ❖ Provide reliable hardware performance but does not characterize operation performance.	❖ System operated under the same control as operated in the buildings. ❖ Provide reliable hardware and operation performance characterization of the tested unit.
	*obstinately considered indispensable to maintain a high accuracy and reproducibility.	*evidence of comparable accuracy and reproducibility have been provided.

Technology Collaboration Programme
by iea

3. Current Standards – Category A

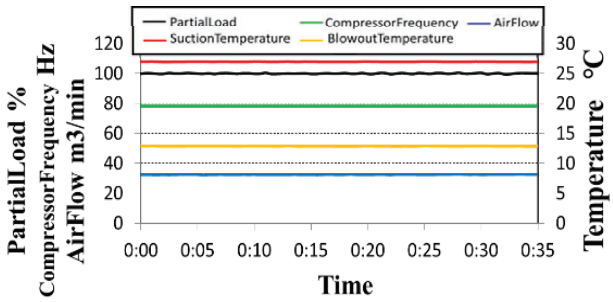
❖ Tests conducted while deactivating native control



$Q_{AC} = const$

*does not represent time-dependent response of the native-control.

Steady-state operation $0 = \sum Q_{BL} - Q_{AC}$



(a) Example of results of JIS test Cooling standard test

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

3. Current Standards – Category A

No.	Title of standard	Year
1	ISO 5151. Non-ducted air conditioners and heat pumps – Testing and rating for performance	2017
2	ISO 13253. Ducted air-conditioners and air-to-air heat pumps – Testing and rating for performance	2017
3	ISO 15042. Multiple split-system air-conditioners and air-to-air heat pumps – Testing and rating for performance	2017
4	ISO 16358. Air-cooled air conditioners and air-to-air heat pumps – Testing and calculating methods for seasonal performance factors – Part 1: Cooling seasonal performance factor, Part 2: Heating seasonal performance factor, Part 3: Annual performance factor	2013
5	EN 14511-1, 2, 3. Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors	2022
6	EN 14825. Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance	2022
7	AHRI 210/240. Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment	2020
8	AHRI 340/360. Performance Rating of Commercial and Industrial Unitary Air-conditioning and Heat Pump Equipment	2022
9	AHRI 310/380. CSA-C744-17. Packaged Terminal Air-conditioners and Heat Pumps	2017
10	AHRI 550/590. Performance Rating of Water-chilling and Heat Pump Water-heating Packages Using the Vapor Compression Cycle	2023
11	AHRI 1230. Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-conditioning and Heat Pump Equipment	2023
12	ANSI/ASHRAE Standard 37-2009 (RA 2019). Methods of testing for rating electrically driven unitary air-conditioning and heat-pump equipment	2019
13	ANSI/ASHRAE 206-2013 (R2017). Method of Testing for Rating of Multipurpose Heat Pumps for Residential Space Conditioning and Water Heating	2017
14	JIS B 8616. Package Air Conditioners	2015
15	JIS B 8627. Gas Engine Driven Heat Pump Air Conditioners	2015

Current rating standards are reviewed in the following aspects:

- ❖ Targeted system,
- ❖ Test method,
- ❖ Test conditions,
- ❖ Unit control during tests,
- ❖ Performance indices and part-load test requirements
- ❖ Tolerance of measurement uncertainty.

Test condition	Dry-bulb (wet bulb) indoor temperature	Dry-bulb (wet bulb) outdoor temperature
Cooling	27 ℃ (19 ℃)	35 ℃ (24 ℃)
Heating	20 ℃ (14.5 ℃)	7 ℃ (6 ℃)
Heating*low T	20 ℃ (14.5 ℃)	2 ℃ (1 ℃)

Test condition	Cooling (heating) capacity (JATL)	Cooling (heating) capacity (Waseda)	Error
Cooling	7038 W	6926 W	-1.6%
Heating	(7845 W)	(7730 W)	-1.5%
Heating*low T	(8927 W)	(8715 W)	-2.4%

Technology Collaboration Programme
by IEA

4. New Testing Methods and Rating Standards – Category B

- Unit set up as in a building installation.
- Unit performance when operated under its native control and using its own thermostat.
- Characterise efficiency losses of variable-speed units. (defrost, on/off cycles, etc.)
- Automated test sequence within a test bin.
- Capture the interaction of the system with building thermal features.
- Prevent manufacturer from artificially inflating the efficiency.

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
ANNEX 88
EBC Energy in Buildings and Communities Programme

4. New Testing Methods and Rating Standards – Category B

Institution	Test scope	Heating conditions	Cooling conditions	Building thermal inertia	3Rs analysis
Waseda University	Emulator-type load-based test for air-to-air units	2 tests defined consistently with JIS B 8515 for heating operation *partial-load at 25% of max capacity **(tentative)	3 tests defined consistently with JIS B 8515 for heating operation *partial-load at 25% of max capacity	Simulated thermal capacitance (sensible and latent) of building interior included in load calculation	Repeatability (completed) Reproducibility (completed) Representativeness (ongoing)
CSA	SPE-07:23 load-based and climate-specific test for air-to-air units (using emulator)	5 temperatures (-15 to 12.2C) plus one additional test for marine climate zone as well as optional test at lowest operating temp	4 temperatures (25 to 40C) plus one additional test for hot, dry climate zone	Simulated thermal capacitance (sensible and latent) of building interior included in load calculation	Repeatability (completed) Reproducibility (ongoing) Representativeness (completed)
BRI / Better Living	Load-based test for VRF air-to-air units	OC: 7C (DBT) 6C (WBT) IC: 20C (DBT) 15C (WBT)	OC: 35C (DBT) 24C (WBT) IC: 27C (DBT) 19C (WBT)	Artificial thermal capacitance (sensible and latent)	Repeatability (ongoing) Reproducibility (ongoing) Representativeness (ongoing)
BAM	Load-based test for hydronic heat pumps	5 or 6 outdoor temperatures in accordance with EN 14825:2022	Not applied yet (ongoing)	Defined within a simplified building model	Repeatability (completed) Reproducibility (ongoing) Representativeness (ongoing)
RWTH	Hardware in the Loop (HiL) for building energy systems with hydronic heat pumps	Outdoor conditions defined by weather data. Use reference days (~4 days) representing a whole year for a specific geographical location	See heating conditions. Depending on location, some days have cooling demand	Simulated by detailed Modelica model of a specific building and system to be studied	Repeatability (completed) Reproducibility (completed) Representativeness (ongoing)
CEPT and RMI	Load-based tests for air-to-air units in humid climates	*To be verified with the research group*	Investigating harmonization across jurisdictions and high humidity conditions	Artificial thermal capacitance (sensible and latent)	*To be verified with the research group*

Technology Collaboration Programme
by IEA

4. New Testing Methods and Rating Standards – Category B - Waseda

Actual air conditioning operation

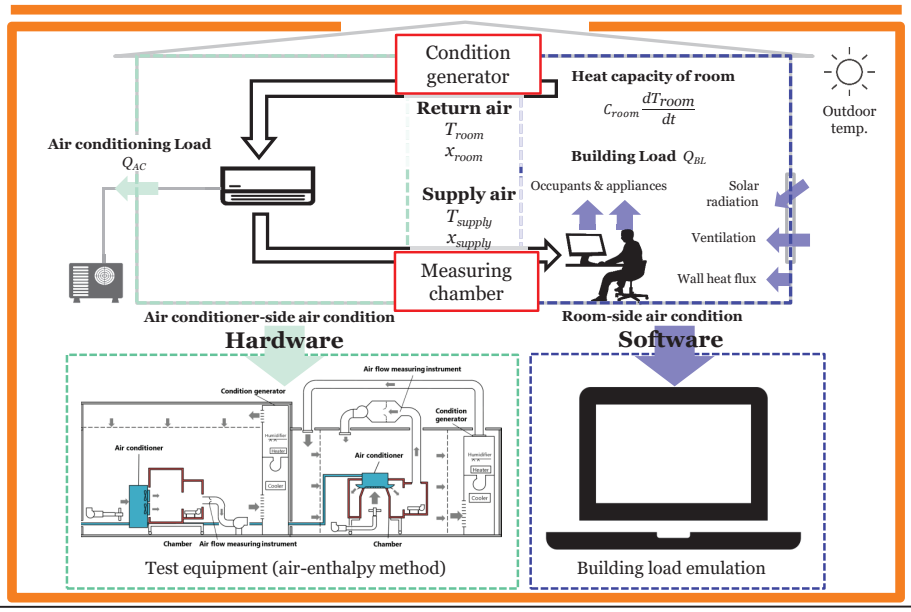
- Different control system response for different building and load features (challenges in reproducibility within different facilities).

Load-based test requirements:

- **Reproduce the room-side conditions.**
- **Measure the dynamic performance of the air conditioner.**

Emulator-type load-based tests

- Air-enthalpy testing equipment used for AC performance evaluation (Hardware).
- Building side conditions delegated to a numerical room emulator (Software).
- Interfaced by condition generator and measuring chamber (A/D converters).



*National project conducted between 2014-2016 for the development of a new testing method able to reproducibly capture the control response of variable speed drive units

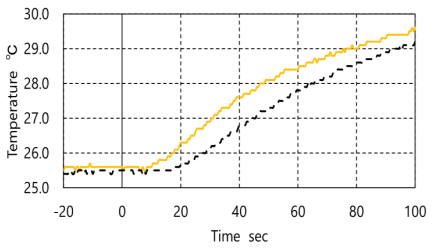
IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
ANNEX 88 EBC Energy in Buildings and Communities Programme

4. New Testing Methods and Rating Standards – Category B - Waseda

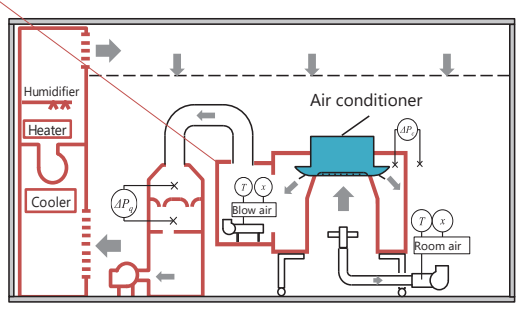
Assess factors that affect trackability and delay in measuring modulations of the supply and return air conditions, to verify suitability to perform dynamic tests.

- **calculation time delay of the emulator; (< 1 s)**
- **time delay of the signal from various sensors;**
- air flow rate and air condition tracking of the measuring chamber;
- temperature and humidity tracking at the condition generator;

②Sensors delay
Sensor response delay **15 sec**
Transportation delay **~15 sec**



(negligible delay compared to the system dynamics)



Reference room thermal time constant ~ 5000 s

4. New Testing Methods and Rating Standards – Category B - Waseda

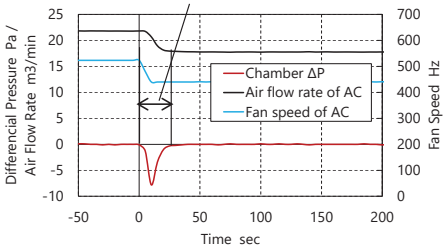
Assess factors that affect trackability and delay in measuring modulations of the supply and return air conditions, to verify suitability to perform dynamic tests.

- calculation time delay of the emulator;
- time delay of the signal from various sensors;
- **air flow rate and air condition tracking of the measuring chamber;**
- temperature and humidity tracking at the condition generator;

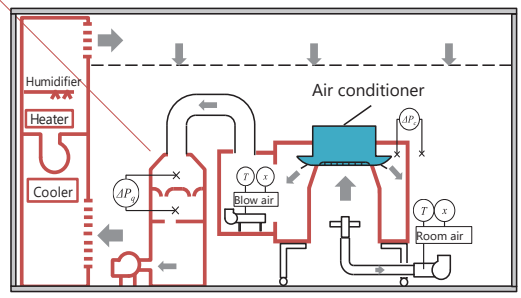
③Air flow measuring point

Differential pressure control delay
25 sec

25 sec



(negligible delay compared to the system dynamics)



Reference room thermal time constant ~ 5000 s

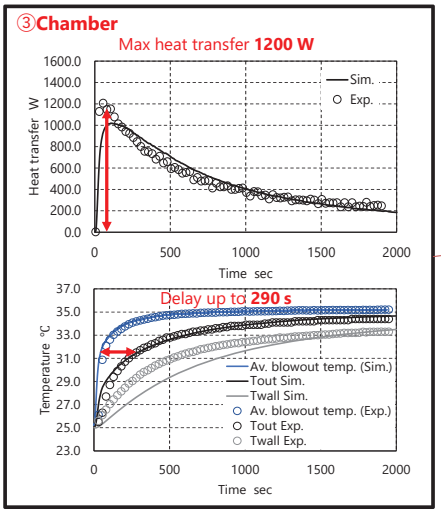
IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

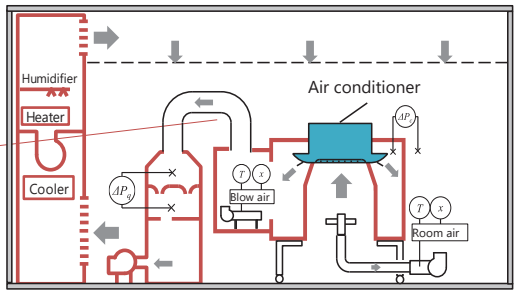
4. New Testing Methods and Rating Standards – Category B - Waseda

Assess factors that affect trackability and delay in measuring modulations of the supply and return air conditions, to verify suitability to perform dynamic tests.

- calculation time delay of the emulator;
- time delay of the signal from various sensors;
- **air flow rate and air condition tracking of the measuring chamber;**
- temperature and humidity tracking at the condition generator;

③Chamber



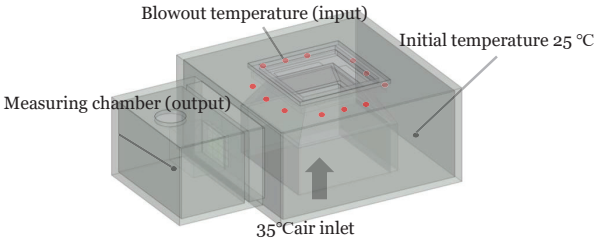


Reference room thermal time constant ~ 5000 s

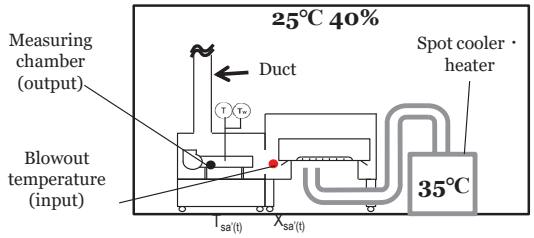
Technology Collaboration Programme
by iea

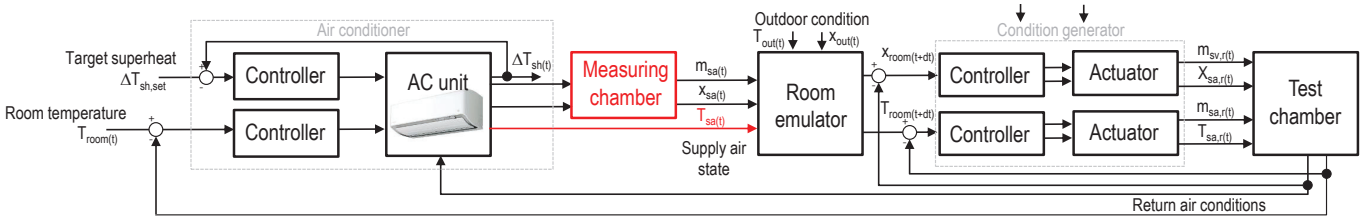
4. New Testing Methods and Rating Standards – Category B - Waseda

Thermal inertia of the measuring chamber is bypassed with a grid of 12 thermocouples



The grid of thermocouples is calibrated to steady-state measurements through the measuring chamber





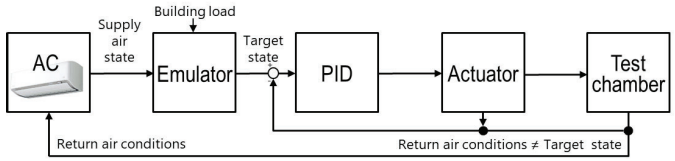
bypassed thermal inertia of the measuring chamber without compromising sensors accuracy

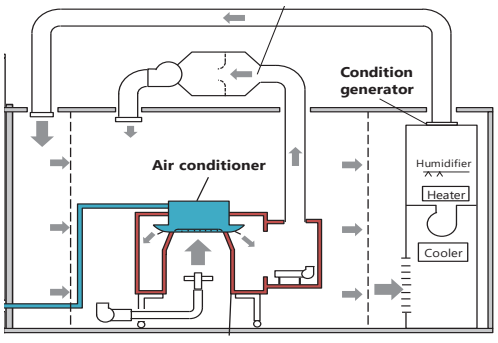
IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
ANNEX 88 EBC Energy in Buildings and Communities Programme

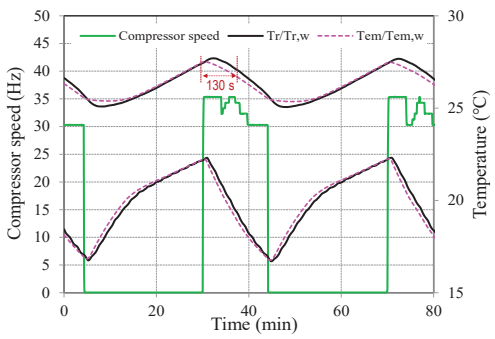
4. New Testing Methods and Rating Standards – Category B - Waseda

Assess factors that affect trackability and delay in measuring modulations of the supply and return air conditions, to verify suitability to perform dynamic tests.

- ❖ calculation time delay of the emulator;
- ❖ time delay of the signal from various sensors;
- ❖ air flow rate and air condition tracking of the measuring chamber;
- ❖ **temperature and humidity tracking at the condition generator;**

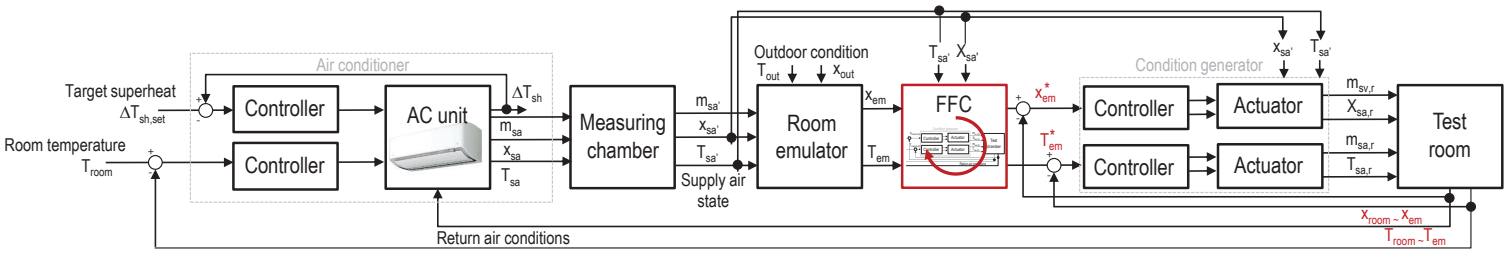




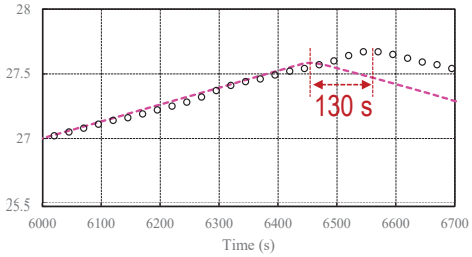


Technology Collaboration Programme
by IEA

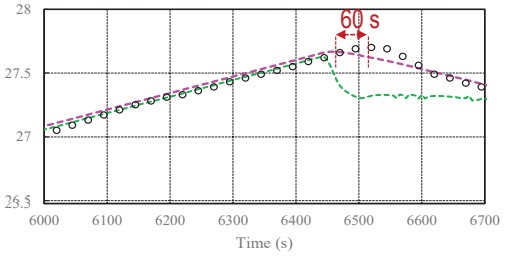
4. New Testing Methods and Rating Standards – Category B - Waseda



$$T^*_{em}(t+dt) = \frac{\frac{T_{em}(t+dt)-2T_{em}(t)+T_{em}(t-dt)}{25} + 0.0053\frac{T_{em}(t+dt)-T_{em}(t)}{5} + 0.00003407T_{em}(t+dt) + 0.028\frac{+2T^*_{em}(t)-T^*_{em}(t-dt)}{25} + 0.0058\frac{T^*_{em}(t)}{5}}{\frac{0.028}{25}+\frac{0.0058}{5}+0.000034082}$$



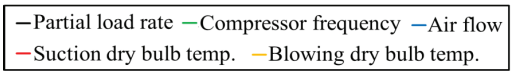
Feed-forward compensation to recalibrate the signal from the emulator and minimize error and delay



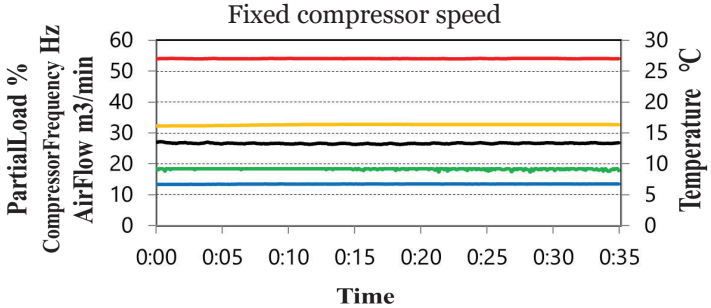
IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

4. New Testing Methods and Rating Standards – Category B - Waseda

LOAD 25%, Indoor 27 °C, Outdoor air temp. 29°C

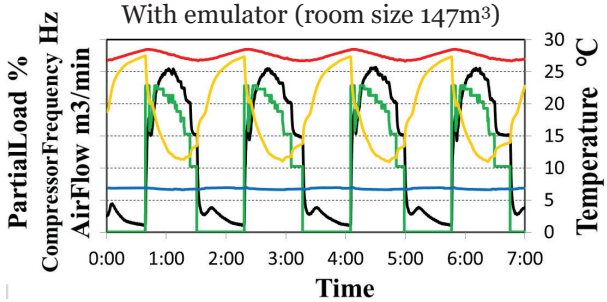


Fixed compressor speed



(COP 7.13)

With emulator (room size 147m³)

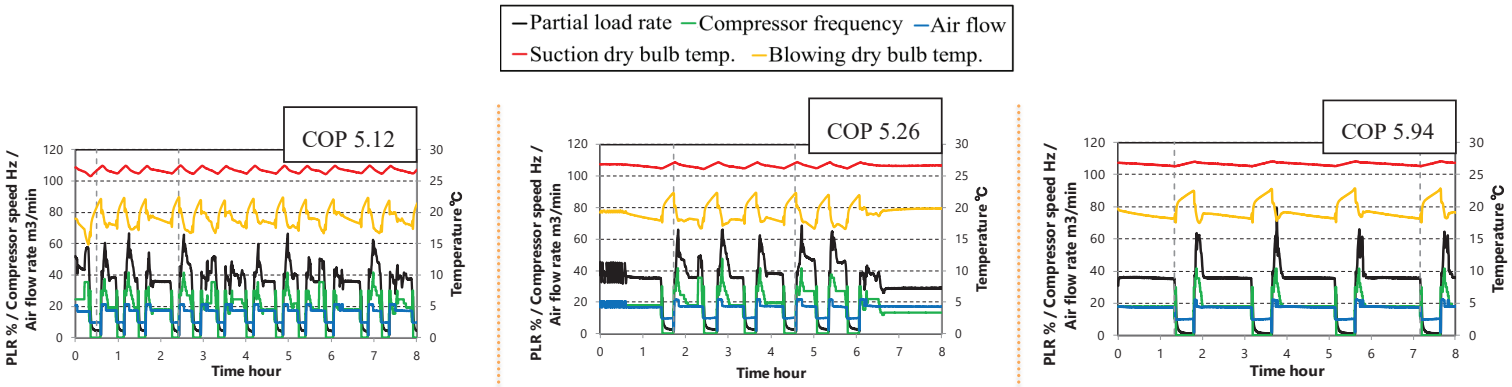


(COP 5.58)

Different performance at corresponding conditions between proprietary- and native- control (approx. 25%)

Technology Collaboration Programme
by IEA

4. New Testing Methods and Rating Standards – Category B - Waseda

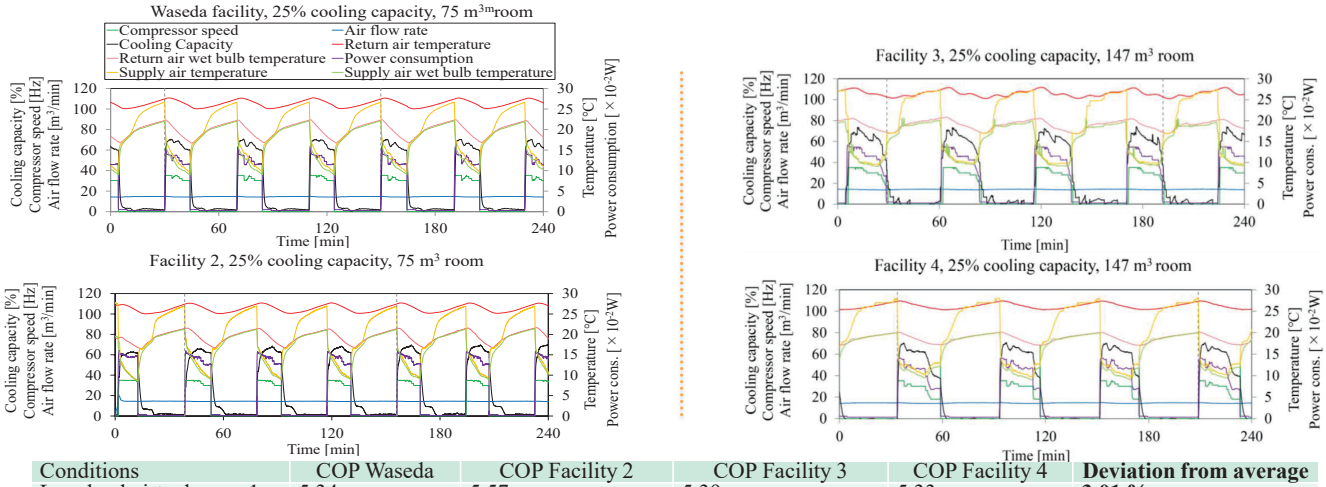


30% Partial load (**75m³**) | 30% Partial load (**147m³**) | 30% Partial load (**300m³**)

- **Freedom to test the system in built environments with different size and characteristics.**
- **Results demonstrate evidence for performance interaction with building features.**

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

4. New Testing Methods and Rating Standards – Category B - Waseda

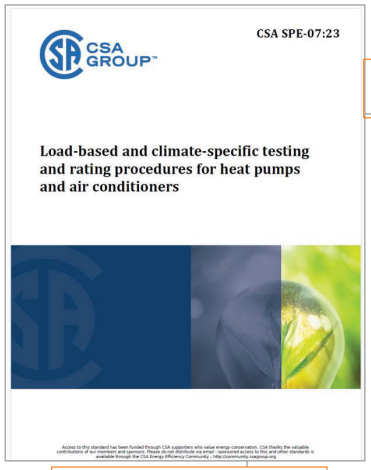


Conditions	COP Waseda	COP Facility 2	COP Facility 3	COP Facility 4	**Deviation from average**
Low load virtual room 1	5.34	5.57	5.39	5.33	**3.01 %**
Low load virtual room 2	5.37	5.22	5.23	5.30	**1.70 %**
Mid load virtual room 1	6.24	6.10	6.04	6.03	**2.25 %**

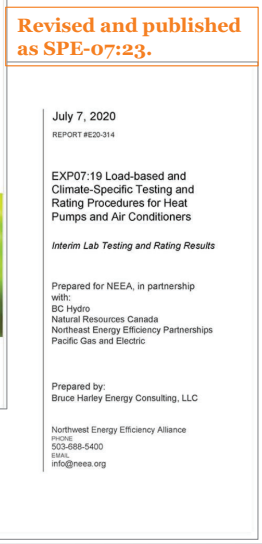
Evidence for similar reproducibility level between Category A and B standards.

Technology Collaboration Programme
by iea

4. New Testing Methods and Rating Standards – Category B - CSA



Technical review version published in 2019.


July 7, 2020
REPORT #E20-314

EXP07:19 Load-based and Climate-Specific Testing and Rating Procedures for Heat Pumps and Air Conditioners

Interim Lab Testing and Rating Results

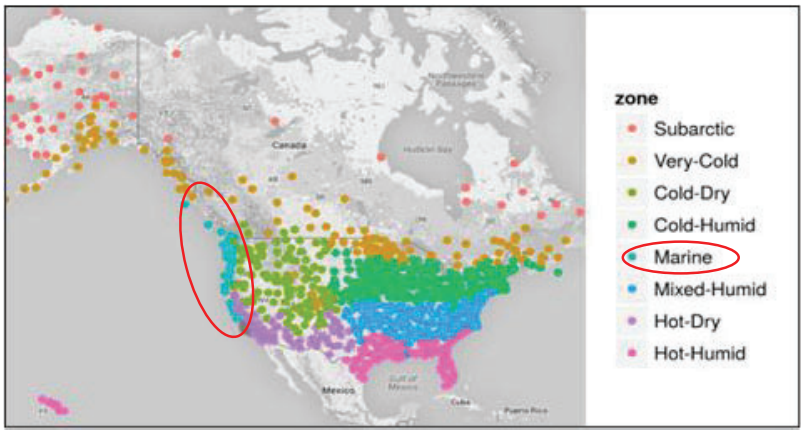
Prepared for NEEA, in partnership with:
BC Hydro
Natural Resources Canada
Northeast Energy Efficiency Partnerships
Pacific Gas and Electric

Prepared by:
Bruce Harley Energy Consulting, LLC

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
EMAIL
info@neea.org

Revised and published as SPE-07:23.

- **Published test method including both test procedures and performance rating calculations.**

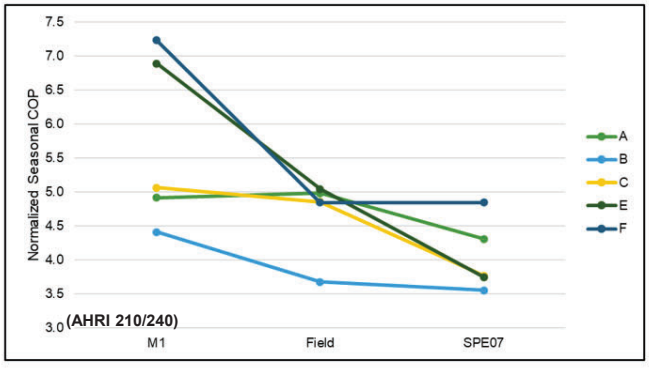


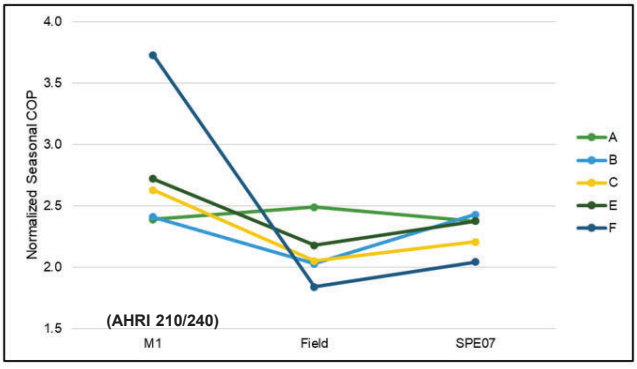
SPE07 uses load-based tests for both heating and cooling operation in order to calculate a set of Seasonal Coefficient of Performance (SCOP) values, for seven different North American climates.

IEA Energy in Buildings and Communities TCP
Annex 88 Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
ANNEX 88 EBC Energy in Buildings and Communities Programme

4. New Testing Methods and Rating Standards – Category B - CSA

Representativeness Study





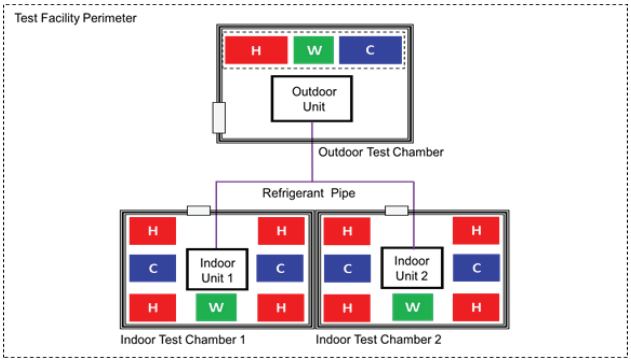
	Cooling RMSE		Heating RMSE		Cooling MAPE		Heating MAPE	
	SPE07	M1	SPE07	M1	SPE07	M1	SPE07	M1
Ducted	0.74	0.45	0.26	0.40	13%	9%	11%	17%
Ductless	0.92	2.14	0.20	1.39	13%	43%	10%	64%
Combined	0.82	1.40	0.24	0.93	13%	22%	10%	36%

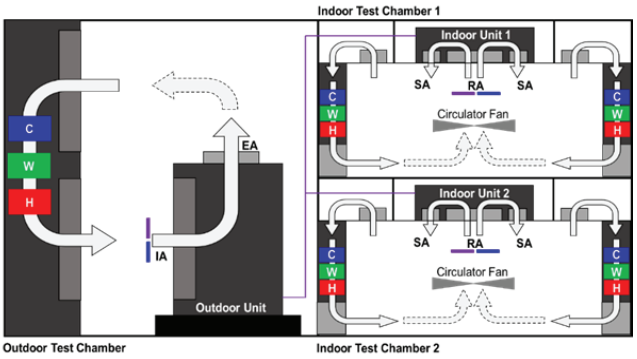
SPE07 results shows smaller errors and better representativeness of field operation.

Technology Collaboration Programme
by iea

4. New Testing Methods and Rating Standards – Category B - Better Living

❖ **The purpose of this proposed test protocol is to improve the testing and evaluation of variable refrigerant flow (VRF) systems, covering especially low partial-load ratio.**

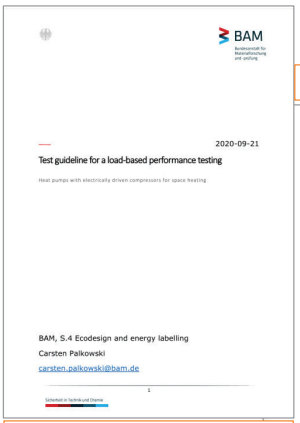




	Heating mode	
	Heating capacity, kW	Power consumption, kW
Catalogue value (rated)	25.00	6.43
Measured value (real)	23.88	6.48

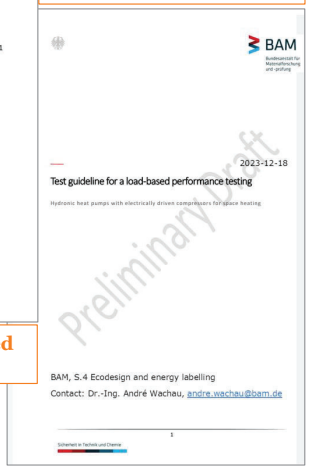
4. New Testing Methods and Rating Standards – Category B - BAM

❖ **The Federal Institute for Materials Research and Testing (BAM) assessed the current standards (EN 14511 and EN 14825).**

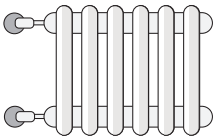


Technical draft published in 2020.

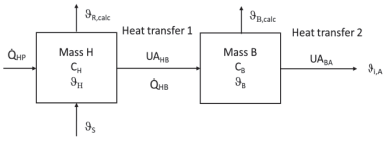
Revised in 2023.



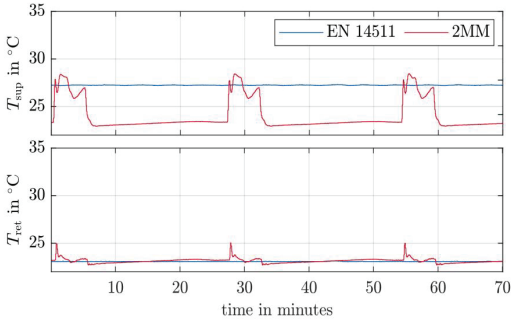
❖ **For hydronic heat pumps**



❖ Method refined with a simplified building model (emulator) for reproducible response in different facilities and enhanced representativeness.

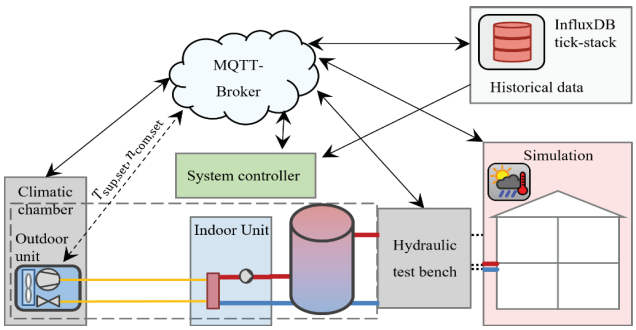


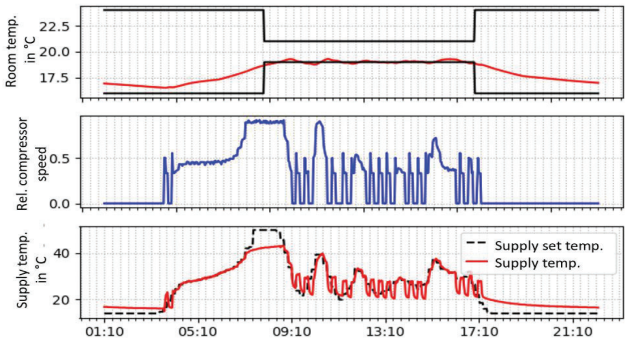
❖ load-based test with active control to overcome issues of current tests.



4. New Testing Methods and Rating Standards – Category B - RWTH

- **The Hardware-in-the-Loop approach couples hardware and software in real-time.**
- RWTH Aachen University developed a method for testing the holistic building energy system, including the hydraulic transfer system, PV-systems or thermal energy storages.
- The building performance simulation is a multi-zone Modelica model.





5. Concluding Remarks and Prospects

- **Testing methodologies provide fundamental measurements for:**
  - Development of effective MEPS
  - Define the basis for performance rating
  - Capturing and verifying design and operation characteristics
  - Stimulate technology developments, evidence-based policies, and guide consumers to beneficial choices.

*The performance of heating and cooling technologies cannot be separated from the building envelope and vice versa.

- **Opportunities from new test methods where systems are operated under the same control as in buildings:**
  - Load based tests rely on the same equipment and instrumentation required by current standards.
  - It can be arguably stated that load-based tests might require more time for test convergence than current standards, but this may be related to the necessary learning curve needed for new procedures
  - Testing heat pumps under the same control as operating in field installations provides opportunities for automating tests
  - Results provide additional value in terms of representativeness of field operation and transparency.

*The review explores potential convergence between product-level performance ratings and building-level energy calculations, simulations, equipment sizing, and policies.