INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

2000-TRP, Develop cost and performance indexes to evaluate effectiveness of virtual airflow meters in HVAC application

Attached is a Request-for-Proposal (RFP) for a project dealing with a subject in which you, or your institution have expressed interest. Should you decide not to submit a proposal, please circulate it to any colleague who might have interest in this subject.

Sponsoring Committee: TC 7.5 - Smart Building Systems

Budget Range: $275,000 may be more or less as determined by value of proposal and competing proposals.

Scheduled Project Start Date: **September 1, 2026,** or later.

All proposals must be received at ASHRAE Headquarters by 8:00 AM, EDT, May 15th, 2026. NO EXCEPTIONS, NO EXTENSIONS. Electronic copies must be sent to rpbids@ashrae.org. Electronic signatures must be scanned and added to the file before submitting. The submission title line should read: 2000-TRP, Develop cost and performance indexes to evaluate effectiveness of virtual airflow meters in HVAC application, and *"Bidding Institutions Name"* (electronic pdf format, ASHRAE's server will accept up to 10MB)

If you have questions concerning the Project, we suggest you contact one of the individuals listed below:

For Technical Matters
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Contractors intending to submit a proposal must notify the Research Administrator by email no later than May 1, 2026. This notification will ensure that any late or additional information regarding the RFP can be provided prior to the proposal's due date. ASHRAE will accept requests for clarifications regarding the RFP through May 1, 2026.

All proposals must be submitted electronically. Electronic submissions require a PDF file containing the complete proposal preceded by signed copies of the two forms listed below in the order listed below. **ALL electronic proposals are to be sent to rpbids@ashrae.org.**

All other correspondence must be sent to ddaniel@ashrae.org. Hardcopy submissions are not permitted. **In all cases, the proposal must be submitted to ASHRAE by 8:00 AM, EDT, May 15, 2026.**
NO EXCEPTIONS, NO EXTENSIONS.

The following forms (Application for Grant of Funds and the Additional Information form have been combined) must accompany the proposal:

(1) ASHRAE Application for Grant of Funds (electronic signature required) and
(2) Additional Information for Contractors (electronic signature required) ASHRAE Application for Grant of Funds (signed) and

ASHRAE reserves the right to reject any or all bids.

State of the Art (Background)

Existing standards, e.g., ASHRAE standards 62.1 (2016a) and 90.1(2016b), set up detailed *advanced energy efficient operations to provide acceptable and healthy indoor environment*. However, some approaches cannot be implemented in HVAC systems because of *the lack of low cost, reliable airflow sensors.* Virtual meters provide an alternative low-cost solution. "Virtual meters" in the context of this document are the results of calculations using the available measured data and mathematical models. The calculations are usually programmed in a Building Automation System or a standalone device. Therefore, the virtual measurements are not from a device assembled and calibrated by a manufacturer and therefore do not have a calibration certification to users.

The concept of virtual sensors has been widely adopted by the automobile industry over the last two decades, e.g., the techniques used to estimate tire pressure by sensing and comparing the rate of each tire rotation (Gustafsson et al., 2001) (Carlson and Gerdes, 2005) (Dementjev, 2007). Virtual meter concepts are not new to the HVAC industry. In 2004, Lee and Dexter [2005] published the development of a fuzzy sensor for measuring the average temperature of the air leaving the mixing-box of an air-handling unit (AHU) because the accuracy of conventional mixed air temperature measurement was limited by space constraints. In their study, a fuzzy relationship between the temperature measured by a conventional sensor and the actual average mixed air temperature was determined through computational dynamic simulations of the mixing chamber, with the results used to correct the errors of the mixed air temperature measured with the conventional physical sensor. Wichman and Braun (2008) further improved the applicability of the virtual mixed air temperature sensor by integrating the temperature calculation with the AHU operational conditions such as outdoor air damper positions. For reliable chiller plant control, an indirect building cooling load measurement was introduced by Huang et al. (2008). In their development, the electricity consumption of the chiller compressors was combined with chiller efficiency models to predict the actual cooling output from the chillers. In addition, Li and Braun [2009] developed a set of virtual sensors for enhancing rooftop AHU operation. For example, the development of a virtual refrigerant charge sensor (Li and Braun, 2009), a virtual refrigerant pressure sensor (Li and Braun, 2009), and a virtual supply air temperature sensor (Yu et al., 2011) has provided a set of low-cost viable methods to better facilitate rooftop AHU optimal operation, fault detection, and diagnosis. In addition, by using pressure drop measurements, valve position, and a calibrated valve curve, a virtual valve flow meter was developed (Swamy et al. 2012; Song et al. 2013). Wang et al. (2018) and Andiroglu et al. (2016) compared the accuracy of the virtual pump meters with the accuracy of conventional flow meters finding that the coefficient of determination or R-squared for the entire validation period is 0.97. Currently, the valve flow meter and pump flow meter are both used for built-up HVAC system fault detection and diagnosis. Rivas Prieto (2017) identified an effective in-site fan curve calibration procedure for virtual airflow meter application.

In summary, virtual sensors currently under development for use in HVAC systems calculate, i.e. indirectly measure, the values for variables that are either too expensive or impossible to measure. The uncertainty of virtual flow rate is propagated from the accuracy of the model and the error of measured inputs through the mathematical models. Although capital costs are generally small, the cost of virtual meters is associated with labor costs for model identification and calibration. Unlike physical sensors, which are characterized by the direct (capital) costs and accuracies given by the manufacturers, there are no standard criteria to characterize and evaluate virtual meters.

Justification and Value to ASHRAE

On average about 30% of building energy use is wasted because of inefficient and faulty system operations. Due to lack of metering capacity in HVAC systems, such energy waste cannot be identified in a timely manner. Virtual sensors provide a low-cost solution for high-resolution metering capacity, enabling the prompt identification of energy waste. At the same time, they enhance operation flexibility and robustness by supporting more advanced automated control and management strategies. Once proven reliable and cost effective, virtual airflow meters will directly contribute to more efficient resource utilization, which is one of the key objectives of ASHRAE's research initiatives. (ASHRAE Research Strategic Plan 2025) As virtual sensors become increasingly available for use in HVAC system control and operations, standard criteria to evaluate the effectiveness of virtual sensors will become an urgent need; this project will satisfy this need. The successful completion of the project will provide virtual-sensor cost and performance evaluation indexes, which are not available today. The outcome of the project will enable sound comparison of virtual and physical sensors for HVAC applications and promote use of virtual sensing technology where it is the most practical and cost-effective sensing option. The broader use of virtual sensors will enhance building monitoring and control and capture energy savings by eliminating waste. Eventually this will contribute towards achieving energy efficiency and sustainability.

Objectives
The objectives to be met by this project are:

1. To identify how virtual airflow meters are evaluated in other industries through a literature survey on virtual airflow sensor uses in general, including in other industries.
2. To categorize different types of virtual airflow sensors based on the amount of independent input variables, parameters and governing equations though a comprehensive study of publications on virtual airflow sensors in HVAC applications.
3. To characterize and evaluate virtual airflow sensors for HVAC applications through the development of appropriate cost and performance indexes.
4. To successfully validate the indexes developed in Task 3 through the development of experimental test procedures and conducting experiments using at least three representative virtual airflow sensors and comparing their performance with high precision physical sensors.
5. To disseminate the research results by documenting the resulting performance indexes for virtual sensor cost and performance evaluations.

Scope:
The project aims at developing matrices for the cost and performance evaluation of virtual airflow meters. Following six tasks are designed to obtain the project objectives.

Task 1: Literature review

In this task, a comprehensive literature review will be performed in the following areas: 1) Virtual airflow meter use in general, including in other industries; 2) Cost and performance evaluation approach/matrices in other industries if available; 3) Virtual meters in HVAC industry with focus on virtual airflow meters.

The deliverable of this task is a report that summarizes the literature review.

Task 2: Categorization of available virtual airflow meter in HVAC industry.

In this task, the available virtual airflow meters in literatures will be categorized based on their working mechanism, such as the amount of independent input variables, parameters and models (governing equations) for the flow rate calculations. Three representative virtual airflow meters will be selected for further study.

The deliverable of this task is a report that summarizes the different types of virtual airflow meters and the three representative meters as candidates for the study.

Task 3: Identify key indexes to evaluate the performance and cost of the three representative virtual airflow meters.

To evaluate performances of the virtual airflow meters, indexes such as physical requirements, complexity of the models, measurement performance, cost of hardware and labor for meter calibration and implementation, and system adoptions etc., need to be identified and defined in this task. The indexes shall be divided into three categories:
a) performance including uncertainties, accuracy and time response, such as time constant; b) indexes that are associated with hardware costs (determined by needed inputs and parameters for the models); and c) indexes that are associated with labor costs in calibration and implementation (determined by hourly costs of different labor categories and total labor hours). The hardware and labor costs are usually related to the model adopted in the virtual flow calculation.

The deliverable of this task is a report defining and summarizing the indexes to be used in the proposed evaluation methodology.

Task 4: Develop experimental test procedures to evaluate the indexes developed in Task 3.

The experimental test is to verify the performance and cost of the selected three representative virtual airflow meters. In this section, the project team is required to make a thorough experiment design plan, so the objectives of the experiments can be served. A total of three types of tests is required, as described below:

1. The uncertainties of the three representative virtual airflow meters must be evaluated, including those arising from the measured input variables used in the models, as well as the models' inherent accuracy. The performance of the virtual flow meters should be compared against high-precision flow meters under both high and low airflow rate conditions. Errors must be reported in both absolute and relative terms for each flow rate scenario. Testing may be conducted in either laboratory (preferred) or field environments, provided that enough flow rate variations are introduced during the tests.
2. Time response tests: Time response is another important characteristic for meters since most meters are applied for control purposes. Therefore, the time response of the three virtual meters needs to be tested with abrupt load changes including fan speed changes and other control signal changes to evaluate the time responses of the virtual airflow meters under both high and low airflow conditions through the comparison with physical flow meters.
3. Repetition tests: The project team needs to propose and justify the number of repetitions for the test purpose.
4. Cost quantification: Costs include the hardware costs and labor cost for the model calibration and implementation. The actual labor effort needs to be documented and recorded to precisely determine the labor costs. Labor categories based on the types of workers or tasks being performed should be defined, such as skilled workers, unskilled workers, administrative staff and management, etc. Labor-related expenses, such as wages, benefits, and taxes based on the geographic area and occupations, are expected to be collected from surveys, government sources, and other publicly available data sources. Then the hourly costs of each labor category and the total labor hours are expected to be quantified to determine the labor cost. The impact by geographic location and other factors on labor cost should be considered.

To successfully execute the three types of tests, the project team is required to design a detailed plan for 1) Test apparatus design and 2) Test procedure design.

The deliverable of this task is a report summarizing the test design and procedures.

Task 5: Test the three representative virtual flow meters and validate them through comparison with the high precision physical flow meters.

Upon approval by the PMS committee of the experimental design, the project team will proceed with equipment installation, testing, and analysis of the experimental results. The experiments are preferred to be conducted in a laboratory environment, where operational variables can be controlled to simulate different flow rate scenarios.

The deliverable of this task is a report summarizing the test setup and test results.

Task 6: Identify and document the resulting performance indexes for virtual meter cost and performance evaluations.

Based on the findings from Task 1 to 5, the project team will identify the key indexes of the virtual airflow meter evaluation matrix. In addition, a standard testing method to obtain the indexes of the matrix is also required for future industry adoption. The project team is also required to analyze the limitation of adopting the indexes and methods to other types of virtual meters if there is any. Suggestions of the future work need to be summarized to address the limitations. It is also expected that the study results will be summarized in Chapter 63-Smart Building Systems of ASHRAE Application Handbook.

The deliverable of this task is a report documenting the indexes, the method and their limitation for other types of the virtual meters.

<u>Deliverables</u>:

Progress, Financial and Final Reports, Research Paper(s), and Data shall constitute the only deliverables ("Deliverables") under this Agreement and shall be provided as follows:

a. Progress and Financial Reports

Progress and Financial Reports, in a form approved by the Society, shall be made to the Society through its Manager of Research and Technical Services at quarterly intervals; specifically, on or before each January 1, April 1, June 10, and October 1 of the contract period.

Furthermore, the Institution's Principal Investigator, subject to the Society's approval, shall, during the period of performance and after the Final Report has been submitted, report in person to the sponsoring Technical Committee/Task Group/Multidisciplinary Task Group (TC/TG/MTG) at the annual and winter meetings, and be available to answer such questions regarding the research as may arise.

b. Final Report

A written report, design guide, or manual, (collectively, "Final Report"), in a form approved by the Society, shall be prepared by the Institution and submitted to the Society's Manager of Research and Technical Services by the end of the Agreement term, containing complete details of all research carried out under this Agreement. Unless otherwise specified, electronic copies of the final report shall be furnished for review by the Society's Project Monitoring Subcommittee (PMS).

Following approval by the PMS and the TC/TG/MTG, in their sole discretion, final copies of the Final Report will be furnished by the Institution as follows:

- An executive summary in a form suitable for wide distribution to the industry and to the public.

- Two copies ; one in PDF format and one in Microsoft Word.

c. Research Paper(s)

One or more papers shall be submitted first to the ASHRAE Manager of Research and Technical Services (MORTS) and then to the "ASHRAE Manuscript Central" website-based manuscript review system in a form and containing such information as designated by the Society suitable for publication. Papers specified as deliverables should be submitted for publication in the Science and Technology for the Built Environment (STBE). The paper(s) shall conform to the instructions posted in "Manuscript Central" for Science and Technology for the Built Environment papers. The paper title shall contain the research project number at the end of the title in parentheses, e.g., (2000-RP). ASHRAE Conference papers are **not** acceptable as deliverables from ASHRAE research projects unless explicitly approved by a vote of the PMS and TC and communicated to MORTS. Conference paper(s) shall conform to the instructions posted in "Manuscript Central" for ASHRAE Conference papers and the title shall contain the research project number at the end of the title in parentheses, e.g., (2000-RP).

All papers or articles prepared in connection with an ASHRAE research project, which are being submitted for inclusion in any ASHRAE publication, shall be submitted through the Manager of Research and Technical Services first and not to the publication's editor or Program Committee.

d. Data

Data is defined in General Condition VI, "DATA".

e. Project Synopsis

A written synopsis totaling approximately 100 words in length and written for a broad technical audience, which documents 1. Main findings of research project, 2. Why findings are significant, and 3. How the findings benefit ASHRAE membership and/or society in general shall be submitted to the Manager of Research and Technical Services by the end of the Agreement term for publication in ASHRAE Insights.

The Society may request the Institution submit a technical article suitable for publication in the Society's ASHRAE JOURNAL. This is considered a voluntary submission and not a Deliverable. Technical articles shall be prepared using dual units, e.g., rational inch-pound with equivalent SI units shown parenthetically. SI usage shall be in accordance with IEEE/ASTM Standard SI-10.

Level of Effort
It is estimated that the project will require two (2) professional months for the Principal Investigator and twenty-four (24) months' effort of a research assistant, with a project duration of twenty-four (24) months at a cost of $275,000.

Proposal Evaluation Criteria
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No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of Work Statement as revealed in proposal	15%
2	Quality of methodology proposed for conducting research.	20%
3	Contractor's capability in terms of technical research skills, critical analysis, industry familiarity, instrumentation, lab or field testing knowledge and accessibility to lab facilities.	30%
4	Qualifications of personnel for this project.	20%
5	Student involvement.	5%
6	Probability of meeting the objectives and schedule of the Work Statement (including past ASHRAE projects, if applicable).	10%

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month
1	Comprehensive literature review report completed	1-4
2	Categorization matrix of available virtual airflow meter technologies finalized	3-6
3	Performance & cost index framework completed	5-8
4	Experimental test procedure manual completed	8-12
5	Validation report for three virtual airflow meters completed	12-20
6	Final performance & cost index documentation delivered	20-24

References:

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2. ANSI/ASHRAE/IES Standard 90.1-2016, Energy standard for buildings except for low-rise residential buildings
3. ASHRAE, 2017 ASHRAE Handbook – Fundamentals
4. ASHRAE Research Strategic Plan, 2021, https://www.ashrae.org/file%20library/technical%20resources/research/research%20strategic%20plan/research-strategic-plan.pdf
5. Andiroglu, E., Wang, G., Song, L., Kiamehr, K. 2016. Development of a virtual pump water flow meter using power derived from comprehensive energy loss analysis. Science and Technology for the Built Environment, Vol 22(2): 214-226.Gustafsson, F. Drev¨o, M., Forssell, U., L¨ofgren, M., Persson, N.,

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8. Huang, G., Wang, S., Sun, Y. 2008. Enhancing the reliability of chiller control using fused measurement of building cooling load, HVAC&R RESEARCH, Volume 14 (6): pages 941-958.
9. Lee, P.S., Dexter, A. I. 2005. A fuzzy sensor for measuring the mixed air temperature in air-handling units, Measurement, Volume 37(1): page 83–93.
10. Li, H., Braun, J.E. 2009. Development, evaluation, and demonstration of a virtual refrigerant charge sensor, HVAC&R RESEARCH, Volume 15 (1): pages 117-136
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15. Rivas Prieto, A., Thomas, W. M., Song, L., Wang, G. 2017. In-situ fan curve calibration for virtual airflow sensor implementation in VAV systems, ASHRAE Transactions, Vol. 123 (1): 215-229.
16. Wichman, A., Braun. J.E. 2009, A smart mixed-air temperature sensor, HVAC&R RESEARCH, Volume 15 (1): pages 101-115.
17. Yu, D., Li, H., Yu, Y. 2011. Virtual calibration of a supply air temperature sensor in rooftop air conditioning units, HVAC&R RESEARCH, Volume 17 (1): pages 31-50.