WORK STATEMENT

TC 8.5 Liquid to Refrigerant Heat Transfer

TITLE
Experimental evaluation of the heat transfer impacts of tube pitch in a highly enhanced surface tube bundle.

BACKGROUND
One of the more common applications of shell-and-tube heat exchangers in the HVAC&R industry is the flooded evaporator. In this type of application, a fluid flows through the inside of tubes and is cooled by the evaporation/boiling of refrigerant on the shell-side of the heat exchanger. In a typical refrigeration cycle application, refrigerant enters the evaporator at a vapor quality greater than zero, generally between 5%-25%. The quality of refrigerant leaving a flooded evaporator typically approaches 100%. Over the course of the last 30 years, the application of flooded evaporators has evolved to use three-dimensional tube surfaces to enhance nucleate boiling. Although relatively simple in its construction, in operation the flooded evaporator exhibits a very complex combination of two-phase flow and heat transfer with phase change.

As a direct result of ASHRAE funded projects, significant experimental data and predictive techniques have been generated for the performance of refrigerant boiling in tube bundles. ASHRAE RP-392, RP-751, RP-977, and RP-1089 all represent significant efforts at advancing the knowledge of heat transfer and flow characteristics associated with boiling in tube bundles, specifically targeting applications in the HVAC&R industry.

Literature published from the work sponsored by ASHRAE RP-392 presents refrigerant-side (external) flow boiling coefficients for the types of tube surfaces encountered in commercial flooded evaporators. Both single-tube and bundle data were obtained for pure refrigerant (R134a, R-11, and R123) using enhanced and integral fin tubes. Gupte and Webb (1992, 1995a, 1995b) presented both experimental data and predictive correlations based on Chen-type superposition and asymptotic models.

ASHRAE RP-751 experimentally demonstrated the effects of oil on boiling in tube bundles. Tatara and Payvar (1999, 2000a, 2000b) present data from integral-finned and enhanced tube bundles, both in pure R-134a and R-123 and with an appropriate miscible oil. For enhanced tube bundles, the study identified significant reduction in heat transfer with the presence of oil.

It is expected that RP-1089 will significantly add to the state of knowledge of evaporation in tube bundles. Variables of heat flux, mass velocity, and quality will all be studied experimentally as independent variables. The study encompasses a matrix of plain and enhanced tube types, a variety of refrigerants (R-134a, R-410A, and R-507A), and includes the effects of oil. In addition to the experimental work, of equal or greater value will be a modeling effort expected to result in general methods that can be used to predict heat transfer coefficients in tube bundles.

Casciaro and Thome (2001a, 2001b) present comprehensive reviews that summarize a large number of relevant studies examining heat transfer, pressure drop, and flow pattern in tube bundles. The surveys reveal a lack of heat transfer models with the ability to predict independent data, very limited research focused on two-phase flow pattern maps in tube bundles, unvalidated shell-side pressure drop models, and inconsistent void fraction prediction methods for tube bundles. In a separate review paper, Browne and Bansal (1999) similarly identify the lack of a “global” boiling model and call for a larger experimental database for boiling in tube bundles. While it is expected that RP-1089 may go a long way towards filling many of these identified gaps in the knowledge base, these reviews identify a general lack of research on heat transfer and fluid flow related to flooded evaporators. This is especially true when compared to the body of literature developed for in-tube boiling and two-phase flow.

The three ASHRAE projects conducted with halogenated refrigerants utilized tube pitch to tube diameter (P/D) ratios of either 1.17 or 1.25, which are representative of the tube pitches commonly used in commercially available flooded shell-and-tube evaporators, such as might be found in a water chiller. Similarly, a majority of the published studies of evaporation of refrigerants on tube bundles have had P/D ratios in the range of 1.15-1.30. Although it does not diminish the importance of existing and ongoing studies, this small range of P/D suggests there may be some limitations to the generality of data and predictive methods generated in these studies.

Although few in number, some studies have examined P/D ratios outside of this range. The study by Jensen, Trewin, and Bergles (1992) included bundles with P/D ratios of both 1.17 and 1.5 in a study of crossflow boiling of enhanced tubes in R-113. They found a slight dependence of heat transfer coefficient on tube pitch when using plain tubes, but only at low heat fluxes (<~10,000 W/m^2). Performance of identical enhanced tubes at different tube pitches was not presented.

A study by Jensen, Reinke, and Hsu (1989) examined plain tube bundles with both staggered and inline tube layouts at a P/D ratio of 1.3, and examined an additional inline tube layout with P/D=1.70. Their experimental apparatus was capable of varying heat flux and mass velocity independently, and they examined local qualities up to 45% using inlet qualities at or near zero. They found little difference in heat transfer coefficients at high heat fluxes, but both tube pitch and layout pattern were significant at low heat fluxes (<~12,600 W/m^2). Also of interest was an observation that the void fraction was dependent on both layout pattern and tube pitch.

Müller (1986) presented tube bundle boiling data for finned tubes at three P/D ratios (1.3, 1.6, 2.0). This author identified a significant impact of tube pitch on heat transfer (lower P/D ratios had higher enhancement relative to a single tube), but the enhancements were most evident at the onset of boiling and at lower heat fluxes (<~10,000 W/m^2). These experiments do not appear to have been run with mass velocity or inlet quality as independently controlled variables.

It is primarily the convective effect of liquid and vapor flowing through the tube bundle that has led to the reporting of bundle heat transfer enhancements relative to single tube boiling in the literature. This convective enhancement is well documented in both plain tube and finned tube bundles. It is this convective effect that can at least qualitatively explain the variation of plain and finned tube bundle performance with tube pitch mentioned in the previous paragraphs. It is generally acknowledged (Casciaro and Thome, 2001a) that convective heat transfer effects in enhanced tube bundles are low relative to nucleate boiling effects, except at low heat fluxes. This has led to the reporting of very low bundle to single tube enhancements for tube bundles utilizing tubes with enhanced three-dimensional surfaces. An exception to this statement is the results presented by Memory, Chilman, and Marto (1994), in which a TURBO-B tube bundle exhibited bundle enhancement factors even at high heat fluxes.

Although representative of the industry, the small range of tube pitch studied experimentally is insufficient to validate models or assumptions about the general effect tube pitch has on flooded evaporator performance. Both new and existing predictive methods that can incorporate tube pitch effects (such as a suitable input to the convective component of a superposition or asymptotic model) cannot be validated due to a lack of data. Particularly absent is data taken using enhanced tubes and refrigerants typical of the HVAC&R industry over a range of tube pitches. Data taken using a wider range of P/D than has been historically used in studies with refrigerant would serve to identify trends (if they exist) associated with tube pitch and could be used to either validate or identify shortfalls in modeling techniques.

Of additional importance to the flooded evaporator designer is the identification of flow phenomena that prevents or limits liquid refrigerant from reaching the surface of an enhanced tube. A disruption in the wetting of a tube surface will lead to reduced heat transfer performance. In the work by Tatara and Payvar (2000a) some unexplained variation in performance from tube row to tube row was reported. In a five-row tube bundle and tests using R-123, the middle of the five tubes was consistently a low performing tube. One explanation for this trend was a hypothesis of reduced tube wetting or partial dry-out due to peculiarities of the vapor flow (the term vapor blanketing was used by these authors). Although flooded evaporator designs can result in a seemingly infinite number of combinations of mass velocity, heat flux, quality and bundle geometry, it is not well established how various permutations might effect the flow path of liquid through a tube bundle operating in a boiling mode. This is supported by the uncertainty of the relationship between quality and void fraction in tube bundles summarized by Casciaro and Thome (2001b). Experimentally, the study of Dowlati et al. (1996) on an R-113 tube bundle showed a significant deviation of an experimentally determined local void fraction from a homogenous void fraction/quality relationship. It is conceivable that a variation in tube pitch could affect the flow of liquid and vapor through a tube bundle sufficiently to affect the wetting and dry-out characteristics of a tube.

ADVANCEMENT TO THE STATE-OF-THE-ART

The background identifies two questions that lack development in the present body of literature regarding evaporation of refrigerants in tube bundles. The first is whether the effect of tube pitch on boiling heat transfer can be simply ignored or accounted for by existing models. Quite simply, there is a general lack of experimental data taken using tube pitches that extend beyond the narrow range of typical industrial application. This implies that while results are certainly relevant to the industry, there is little information as to the range of applicability of existing data and models.

The second question is the quantification of specific flow and bundle parameters that lead to dry-out or localized reduced wetting of tubes in an evaporating tube bundle. Refrigerants with high ratios of vapor volume to liquid volume (such as R-123) and large tube bundles are thought to be particularly susceptible to bundle wetting effects.

The study described in this work statement would serve to address these two questions and guide the design and application of flooded evaporators throughout the HVAC&R industry.

JUSTIFICATION AND VALUE TO ASHRAE

Fundamental understanding of boiling in tube bundles and comprehensive predictive models form the basis from which flooded evaporators are designed across the HVAC&R industry. It is envisioned that the results generated by the work described in this document would serve to validate existing and future modeling techniques and simultaneously expand fundamental understanding by examining a variable often overlooked in both the scientific study and design of flooded evaporators (tube pitch).

Focusing on the effect of tube pitch and localized wetting is driven primarily by the application of a large flooded evaporator such as would be found in larger commercial air conditioning or refrigeration applications. The equipment typical to this type of application has among the highest initial costs and the highest energy utilization of any in the HVAC&R industry. ARI statistics suggest the global market size for centrifugal chillers with cooling capacities over 500 tons can be estimated at approximately $390 million for 2004. This represents a significant investment by much of the ASHRAE community, including both manufacturers who design and manufacture the equipment and by customers who purchase it. In addition, the energy costs associated with operating this type of equipment over a 20-25 year life cycle will typically be much greater than the initial capital expense. By further improving the understanding of boiling in tube bundles, it will be possible for equipment manufacturers to improve both design methods and equipment that utilizes flooded evaporators. Because of the magnitude of the costs (both direct and long term energy costs) associated with this equipment, even incremental improvements in evaporator design can provide tangible benefits. These benefits extend through ASHRAE and beyond by allowing the construction and installation of more efficient HVAC&R equipment at a constant cost or lower cost equipment at the same efficiency level.

OBJECTIVE

The objective of the research defined by this work statement is to examine the refrigerant-side heat transfer performance of boiling in tube bundles, quantifying trends with respect to tube pitch. The influence of heat flux, mass velocity, and vapor quality are to be included in the study. The effect of these variables on surface wetting of tubes should also be assessed.

SCOPE

The study should follow the general guidelines given below:

1. There shall be a minimum of three test sections, consisting of a simulated horizontal bank of 3/4" nominal diameter tubes, each using a staggered triangular pitch. One section should have a standard, 7/8" (P/D = 1.167) triangular pitch. The remaining sections shall be at different triangular tube pitches proposed by the investigator based on a review of relevant work, and approved by the Project Monitoring Subcommittee (PMS). It is suggested that the study would examine a range of tube pitches up to 1.75 inches (P/D = 2.33). Tubes used for test purposes shall be commercially available and shall have an enhanced, structured, three-dimensional surface (no more than one tube type per refrigerant). The specific surface type will be determined by the PMS.

   Each test section must be instrumented to measure local (multiple individual tubes) and overall bundle heat transfer coefficients in flow boiling. The test facility should include the capability of independently varying heat flux and mass velocity. This capability removes the interdependence of multiple variables of interest and facilitates interpretation of results. Independent heat flux and mass velocity variation implies that the test section should include overfeed capability in which unevaporated liquid refrigerant is allowed to leave the test section. Test section construction must minimize the potential of the refrigerant exit flow from affecting flow through the tube bundle.

   The test sections will have provisions for the introduction and distribution of refrigerant liquid-vapor mixture below the lowest row of tubes. The walls of the test section must be so configured as to promote cross sectional flow uniformity, minimizing effects of the test section walls on flow through the tube bundle. The test section must be constructed and operated (using refrigerant inlet flow conditioning and potentially tube-side fluid flow parameters) to minimize axial variations of heat flux, mass velocity, and inlet quality down the length of the tube bundle and promote two dimensional flow in the test section.

   The active test section shall be at least eight rows deep. However, preference will be given to investigators proposing larger (increased number of rows) test sections, as large tube bundles is the area of application that is of most interest. The facility should be capable of handling dry-out or near dry-out conditions within the test section.

Data reduction may rely upon either a surface temperature approach or an LMTD type analysis, although an LMTD analysis with tube-side fluid flow is preferred. In either case, the experimental uncertainty of the shell-side heat transfer coefficient shall be no greater than 10% at a heat flux of 10,000 Btu/hr-ft^2 (31,540 W/m^2). If tube-side fluid flow is used, this requires that an accurate tube-side heat transfer coefficient correlation be used. This necessity may preclude the use of some vendor-supplied correlations. The method of tube-side heat transfer coefficient calculation should be documented in the proposal and approved by the PMS prior to the commencement of experimental work.

Specific details, including basic dimensions, instrumentation/measurement methods, and data reduction methods shall be described in all proposals. Sufficient detail to demonstrate compliance with the requirements of this work statement shall be included.

2. A refrigerant flow loop is required to provide a source of 40°F (4.4°C) saturated liquid and vapor to the evaporator test section. The refrigerant supplied to the test section shall be free of lubricants. The flow of liquid must be sufficient to operate each test section at heat and flow capacities that satisfy the suggested range of heat flux and mass velocity given in this work statement. The loop should include the capability to vary the inlet vapor quality from near zero to a minimum of 25%. Higher inlet qualities may be required to cover the entire range of test conditions.

3. The experimental test matrix should be developed with the application of a large flooded evaporator (20+ rows) in mind. In such an application, global variables such as bundle average heat flux and average mass velocity vary from application to application dependent on heat exchanger geometry and operating conditions. In addition to these global variations, local heat fluxes and local vapor quality within the bundle vary greatly. For this study, it is envisioned that each full test bundle operating point will generate a set of data with a variety of local conditions. The number and range of the local data points will be dependent on test section construction and operation. In terms of defining an experimental test matrix, global operating points must be defined that create local data of sufficient number that they resolve the effects of the variables over the ranges of interest. The following tables provide general guidance for the creation of an experimental test matrix. The test plan shall include both R-134a and R-123. The final experimental test matrix should be generated by the Principal Investigator and approved by the PMS prior to conducting any tests.

"Global" Variable	**Suggested Number of Variations**
Bundle Average Heat Flux	5 – 9
Mass Velocity	3 – 6
Inlet Quality	2 – 4
Tube Pitch	3 – 5

"Local" Variable	Suggested Range
Local Heat Flux	1,000 - 25,000 Btu/hr-ft^2 (3150 – 78,850 W/m^2)
Mass Velocity (Based on minimum flow area between tubes)	5,000 - 38,000 lbm/ft^2-hr (6.78 – 51.5 kg/m^2-s)
Local Vapor Quality	0.0 - ~1.0 (dry-out)

4. Depending on test facility design, it may be appropriate to determine sensitivity to refrigerant charge within the test section and/or optimize operating charge for certain test conditions. At a minimum, additional tests are recommended in order to check the applicability of test results to a flooded bundle application. Such a test requires that the experimental test section be operated with the mass flow rate of evaporating refrigerant exactly equal to the mass flow rate of liquid refrigerant entering the test section (vapor quality = 1.0 at refrigerant exit). The amount of refrigerant "charged" into the test section under these conditions should then be varied to maximize the average shell-side bundle heat transfer coefficient without allowing any liquid refrigerant to leave the bundle. This configuration will simulate a typical flooded bundle application. Local experimental data can then be taken and compared to results generated by the more systematic, independent variable based experimental plan to verify consistency and applicability of the results. These tests should be conducted at bundle average heat fluxes of approximately 5,000 Btu/hr-ft^2 (15,770 W/m^2) and 10,000 Btu/hr-ft^2 (31,540 W/m^2), with a refrigerant inlet quality of approximately 15%.

5. Qualitative assessment of the two-phase flow pattern over the conditions summarized above for each test section (tube pitch) is a requirement. This will require the test section to have optical access in the form of viewports, sightglasses, or partial construction with transparent materials. Observations should be recorded by photograph, video, or other optical means and compared to published flow regime maps. It is expected that "visual" data may prove useful in explaining experimental trends. Of specific interest are observations of partial or complete dry-out of tubes. Novel or advanced visualization methods that can be used to supplement trend explanations are encouraged but not required. Potential flow visualization techniques should be described in all proposals. Pending outcome of the testing, the PMS may request visual material in a format that is suitable for publishing in the electronic versions of the ASHRAE handbook.

6. Heat transfer results for each refrigerant test series should be plotted as a function of the relevant input variables, with special attention given to the effects of tube pitch and the onset of dry-out or partial dry-out conditions. Although this study is primarily experimental in nature, fundamental descriptions and explanations of experimental trends shall accompany the final documentation of the study. Experimental data should be compared to appropriate results of published analytical methods, specifically (but not limited to) those methods resulting from work undertaken as part

of RP-1089. If limitations of existing predictive methods are identified, enhancements or improvements should be suggested. It should be noted that additional testing or measurements (i.e. single tube pool boiling tests, determination of void fraction, etc.) may be required in order to satisfy all of the inputs to appropriate bundle heat transfer prediction methods.

DELIVERABLES

1. Progress and Financial Reports
   Progress and Financial Reports, in a form approved by ASHRAE, 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.

   Additionally, the Institution's Principal Investigator shall, during the period of performance and after the Final Report has been submitted, report in person to the sponsoring Technical Committee (TC) at the annual and winter meetings, and be available to answer such question regarding the research as may arise. Because frequent PI/PMS interaction is desirable, informal email messages summarizing project status should be sent to PMS members on a monthly basis.

2. Final Report
   A Final Report, in a form approved by ASHRAE, shall be prepared 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, six copies of the final report shall be furnished for review by the Society's Project Monitoring Subcommittee (PMS).

   The Final Report shall include:
   -Background/Literature Survey
   -Experimental Uncertainty Analysis
   -Appropriate results as described in the Scope of this work statement
   -All experimental data in tabular form
   -Suitable reproductions of flow visualization photographs or visual recordings

   Following approval by the PMS and the TC, 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 bound copies
   -One unbound copy, printed on one side only, suitable for reproduction.
   -Two copies on disks; one in PDF format and one in Microsoft Word.

3. Technical Paper
   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 presentation at a Society meeting. The Technical Paper(s) shall conform to the instructions posted in "Manuscript Central" for a technical paper. The technical paper title shall contain the research project number (xxxx-RP) at the end of the title in parentheses, e.g., (9999-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.

4. Data
   Data as defined per General Condition VI, "DATA," will be maintained on file for a period of two years after receipt of final payment. Upon request, the Institution will make a copy of this data available to the Society during this period.

All documents 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 expected that this project will take 30 months to complete at an estimated cost of $190,000. This time estimate includes approximately 15 months for background development/facility construction/test definition, approximately 9 months for data collection, and 6 months for data analysis and documentation. Approximately eight person-months of the Principal Investigator and thirty person-months of a research assistant are estimated. The estimated costs include $165,000 for personnel (PI, research assistant, technicians, etc.), $15,000 for equipment and test fluids, and $10,000 for administrative and other miscellaneous costs.

ADDITIONAL INFORMATION FOR BIDDERS
It is expected that those bidding for this project will have basic capabilities (refrigerant flow loop) for performing refrigerant heat transfer studies. The project should not include funds to develop this capability.

The intent of this study is to supplement and extend the work conducted in previous ASHRAE and academic studies by examining a combination of variables and refrigerants not specifically targeted by previous work. In terms of recent work, the final report of RP-1089 should be thoroughly reviewed prior to the initiation of a new study. This report, as well as those from RP-751 and RP-392 would be particularly appropriate references for preparing an experimental plan in terms of facility, measurement techniques, and instrumentation.

Although not included in the scope of this study, investigators are encouraged to make basic provisions for the inclusion of oil in test facilities. Had they been included, oil/lubricant effects would have been expected to influence the results of the testing. The potential impact of oil on the results of the work conducted in this study may form the basis for follow-up research.

PROPOSAL EVALUATION CRITERIA

Proposals submitted to ASHRAE for this project should include the following minimum information:

1. Statements describing test facilities, equipment, capabilities, procedures, methods, etc., to be used to meet the objectives defined in this work statement.
2. Statements indicating experience in conducting research related to boiling heat transfer and two-phase flow.
3. Resumes of the principal investigator and others involved in the study.
4. Planned schedule and length of time for the project to be completed.
5. Budget information.

Proposals will be evaluated on:

1. Contractor's understanding of Work Statement as revealed in proposal. 10%
2. Quality of methodology proposed for conducting research. 25%
3. Contractor's capability in terms of facilities. 20%
4. Qualifications of personnel for this project. 15%
5. Student involvement. 2%
6. Probability of contractor's research plan meeting the objectives of the Work Statement. 20%
7. Performance of contractor on prior ASHRAE projects or other energy projects. (No penalty for new contractors) 8%

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AUTHORS

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