WORK STATEMENT
from
TC 8.5 Liquid to Refrigerant Heat Transfer

TITLE

Flooded evaporation heat transfer performance investigation for tube bundles including the effects of oil using R-410A and R-507A.

BACKGROUND

Characterization of flooded evaporation heat transfer performance for tube bundles has been an active area of research within ASHRAE over the past decade. Two separate research projects were conducted each generating a significant amount of useful data for heat exchanger designers in the HVAC industry; namely, Research Projects 392 and 751 (RP-392 and RP-751).

RP-392 focused on the characterization of boiling heat transfer performance for flooded tube bundles using pure refrigerants. Single-tube data were taken in parallel with high quality bundle data to allow for direct comparison. Gupte and Webb (1992, 1994) proposed modified Chen superposition and asymptotic models capable of predicting the bundle performance data generated in RP-392 for the most part within a 20% error band. Refrigerants R-134a, R-11, and R-123 were evaluated using tube bundles manufactured with enhanced boiling and integral-fin tubes.

Another significant tube bundle investigation conducted using a pure halocarbon refrigerant (R-113) is the study performed by Jensen, Trewin, and Bergles (1992). Tests were performed using bundles manufactured with plain and enhanced boiling tubes. The enhanced boiling tubes yielded heat transfer coefficients that did not vary significantly with either vapor quality or mass velocity.

The effect of oil on tube bundle heat transfer performance is of great interest, because large refrigeration equipment is typically designed such that a small amount of oil circulates throughout the system. For a machine equipped with a flooded evaporator, which is the design typically preferred for large high efficiency equipment, the oil concentration is significantly greater in the evaporator than that at any point upstream in the system. Centrifical chillers operate at Air-Conditioning & Refrigeration Institute (ARI) full load rating conditions with oil concentrations well less than 1% by mass fraction in the evaporator, if measurable at all, but systems equipped with positive displacement compressors, depending upon vendor and specific design, may see oil concentrations as high as 10% and greater.

Thome discusses the effects of oil upon shell-side boiling in a 1996 state-of-the-art review paper (Thome, 1996). Oil impacts the heat transfer coefficient via three separate mechanisms: mass transfer effects; change in physical properties of the fluid; and a modification to the underlying physical heat exchange process. As the more volatile component evaporates, a rise in bubble point temperature occurs at the liquid-vapor interface, which decreases excess temperature at the surface (T_{wall} - T_{bubble}), thus negatively impacting heat transfer performance. Surface tension, viscosity, and bubble contact angle each vary with local oil concentration and have significant influence on heat transfer coefficient. In addition, oils promote a foaming phenomenon at the heat transfer surface. Foaming does modify the physical boiling process affecting parameters such as mean bubble diameter and site density.

Although a significant number of heat transfer studies focusing on oil effects have been conducted over the past several decades, it is still very difficult to predict specifically how a given oil will impact shell-side boiling coefficient. The following parameters must be considered when estimating how a given oil may impact shell-side heat transfer performance: thermodynamic and transport properties for the refrigerant; thermodynamic and transport properties for the oil; oil concentration; heat flux; saturation conditions;

solubility and miscibility characteristics of the refrigerant/lubricant mixture; surface geometry; bundle configuration (tube diameter and bundle layout); refrigerant mass velocity and quality; and bundle size (pool depth). Because accurate analytical techniques do not exist today, researchers and designers are forced to experimentally evaluate combinations of the parameters of influence to the heat transfer process. One study intending to support this effort was RP-751, which is just coming to completion.

RP-751 augmented RP-392 with the inclusion of oil effects. Miscible oils were evaluated with refrigerants R-123 and R-134a using tube bundles manufactured with integral-fin and enhanced boiling tubes. Unlike RP-392, RP-751 focused exclusively on the generation of experimental data, not the development of performance models, such as those capable of accounting for the effects of miscible oil upon bundle shell-side heat transfer coefficient. It should be noted that the author of this work statement does not intend to diminish the value of an empirical study like RP-751, merely note that data from such a study serve only as an intermediate step until more general semi-empirical models come available. With the near completion of RP-751, it is opportune for a follow-up study to be conducted that focuses heavily on the development of semi-empirical boiling models.

Another tube bundle heat transfer study conducted using a miscible oil was presented by Memory, Akcasayer, Eraydin and Marto (1995). R-114 was evaluated with a miscible oil using tube bundles manufactured with smooth, integral-fin, and enhanced boiling tubes. It was demonstrated that oil concentrations as high as 10% yielded heat transfer coefficients higher than those measured with the pure refrigerant for both the plain-surface and integral-fin tube bundles, while the enhanced boiling tube bundles only suffered heat transfer performance penalty with the inclusion of any amount of oil. Similar oil effects were also demonstrated with enhanced boiling tubes in a single-tube study performed by Webb and McQuade (1993).

R-134a currently appears to be a very attractive choice for the replacement of R-22 in large refrigeration equipment, but other possible candidates, such as R-410A and R-507A, should at least be evaluated on a small bundle scale. R-410A, only having a temperature glide of less than 0.2°F at evaporator saturation temperatures of practical interest, is none-the-less classified as a zeotrope. R-507A is classified as an azeotrope. Both R-410A and R-507A offer a lower ideal COP than either R-134a or R-22, but this disadvantage is partially offset with a lower gas specific volume, which equates to lower pressure drop in connecting piping and in the flow areas of the heat exchanger itself. A lower system pressure drop mitigates the ideal COP shortfall to some degree. In addition, lower specific volume for the gas equates to a smaller compressor yielding direct savings in both mass and cost. R-410A, but not R-507A, is also attractive considering that it has a larger latent heat of vaporization than R-134a, which should lead to a smaller volumetric flowrate of refrigerant for a given operating capacity.

Recent single-tube heat transfer performance experiments using pure R-507A have been performed by Koster, Herres, Kaupmann, Hubner, and Gorenflo (1996) and Spindler, Voss, and Hahne (1996). Data taken thus far indicates nucleate boiling heat transfer coefficient for this fluid to be comparable to that of R-134a.

Single-tube pool boiling heat transfer experiments with a nearly azeotropic mixture of R-32/R-125 (60/40) were reported by Chen and Tuzla (1996) and Thors and Hemdon (1993). A 60/40 composition is not far from the current composition of R-410A, which is 50/50, respectively for R-32/R-125. The composition adjustment from 60/40 to 50/50 occurred in the recent past due to flammability concerns -- R-32 is flammable. In the Chen and Tuzla (1996) investigation, a mixture of R-32/R-125 and an ester oil, 5% by weight, yielded higher heat transfer coefficients than those for a 5% by weight mixture of R-22 and a petroleum based lubricant.

In summary, tube bundle heat transfer performance data for refrigerants R-410A and R-507A are not available in the open literature. In addition, semi-empirical heat transfer performance models for use with flooded evaporator tube bundles which can account for the effects of oil need to be created. Availability of these performance models will be of direct use to heat transfer design engineers in the HVAC industry.

JUSTIFICATION

Correlations for the prediction of flooded evaporation tube bundle performance exist, but currently do not allow for the effects of miscible oils to be taken into account. For water chillers designed with positive displacement compressors, if oil separation is not 100% efficient, the influence of oil upon heat transfer performance and unit efficiency is typically significant. Until state-of-the-art compressor technology offering "oil-free" bearings is available in the market, heat transfer research must continue with the characterization of these oil effects.

RP-751 generated useful heat transfer performance data using bundles manufactured with commercially available tubes, refrigerants of practical interest, and appropriate oils for each refrigerant evaluated. RP-751 data does allow for heat transfer engineers in industry to make educated engineering decisions in the design of new equipment and retrofit of existing products. However, semi-empirical heat transfer correlations, similar to those proposed by Gupte and Webb (1992, 1994) in technical papers resulting from RP-392, are yet to be generated.

The research project described herein augments RP-392 and RP-751 with a two-fold benefit. First, tube bundle heat transfer performance data will be generated with refrigerant blends of commercial interest. Like RP-751, the effects of miscible oils will be taken into account during this phase of the work. Second, the current study will focus on the development of semi-empirical and/or analytical correlations for use by heat transfer engineers in industry. For the generation of heat transfer performance models, investigators in the proposed research program will take into account performance data generated in RP-392 and RP-751, as well as any other flooded evaporation tube bundle study deemed useful by the Project Monitoring Subcommittee (PMS).

OBJECTIVE

a. Undertake a literature survey on horizontal shell-side boiling, especially in the area of air-conditioning and refrigeration applications.

b. Perform both single-tube and tube bundle experiments with R-22, R-410A, and R-507A using at least one saturation temperature and enough flow and quality conditions to establish performance trends.

c. Quantify the effects of miscible oil upon shell-side heat transfer coefficient.

d. Develop semi-empirical and/or analytical correlations suitable for use by design engineers, and submit these correlations for publication in the appropriate ASHRAE handbook.

SCOPE

Task I - Literature Search

A literature search shall be performed in an effort to review techniques for modeling shell-side flooded evaporation heat transfer performance. The proposed method(s) for presenting and correlating heat transfer data shall be included in the proposal. Particular focus should be given to how the effect of oil will be accounted for in the resulting correlations.

Task II - Experimental Effort

Heat transfer experimental facilities shall be capable of meeting the following test conditions:

Average bundle heat flux - 1,000 to 20,000 Btu/h-ft^2 (3.2 to 63.0 kW/m^2)

Refrigerants - R-22, R-410A, R-507A

Quality range to be evaluated - 0.0 to 0.9

Range of mass velocity (based upon min flow area) - 5,000 to 20,000 lbm/ft^2-hr (6.78 to 27.1 kg/m^2-s)

Tube diameter - 0.75 inch (19.1 mm)

Bundle layout - 0.875 inch (22.225 mm) triangular pitch

Saturation Temperature - 40 °F (4.4 °C)

Prior to conducting any experimental tests, a test matrix shall be generated by the Principal Investigator and submitted to the PMS for approval. The test matrix will comply with the range of test conditions listed above. The PMS will review the test matrix paying particular focus to the ability of the proposed work to generate sufficient data for the generation of boiling models. It is anticipated that several iterations between the PMS and the Principal Investigator may be required prior to finalizing the experimental test matrix.

Please note, the intended project focuses on simulating a large horizontal flooded evaporator by taking data at a variety of refrigerant quality, mass flux, heat flux, and oil concentration combinations using a relatively small experimental tube bundle. It is not the intent of this research program to conduct flooded evaporator tests with the small experimental tube bundle. In order to simulate a large bundle, the small bundle will operate at conditions where both refrigerant liquid and refrigerant vapor exit at the top of the test section. Care must be taken in the design of the test section in order for a two-phase mixture (three-phase considering any oil present) to exit at the top of the bundle without “stratifying” -- stratifying would allow refrigerant liquid and/or lubricant to fall back into the test section, hence corrupting the data.

Exact dimensions of the test section should be described in the proposal. The tube bundle should have a minimum of seven rows of depth and a triangular-pitch tube alignment (staggered alignment). The uncertainty of the shell-side coefficient measurement must be no greater than 8.0% at a heat flux of 10,000 Btu/[hr-ft^2] (31.6 kW/m^2) A tube length of 42 inches (1.07 meters) or more should be used to achieve this measurement accuracy. One or two passes, but no more than two, through the tube bundle for the tube-side fluid are desired. The test section should be equipped with sight glasses to allow for visual observations.

A comprehensive description of the test facility including instrumentation should be provided in the proposal. The measurement of parameters which influence the shell-side coefficient shall be described in detail, including the following items: temperature, pressure, liquid flowrates, energy transfer rate, refrigerant composition, and oil concentration. Particular focus should be given to the proposed method for determining the oil concentration in the tube bundle, as well as describing the technique for introducing oil into the refrigerant stream.

How the tube-side heat transfer coefficient will be determined for the tubes evaluated in this work should be described in detail. Use of vendor supplied heat transfer correlations is deemed unfavorable with preference given to those researchers proposing to determine the tube-side heat transfer performance experimentally. Entrance effects associated with testing tube lengths considerably shorter than those typically found in industry will be accounted for using this approach.

All surfaces evaluated in this research program will be commercially available for purchase by any Original Equipment Manufacturer. The specific surfaces to be tested will be decided upon by the PMS (PMS membership includes representatives from three different large HVAC equipment manufacturers). The following table presents surface testing requirements for this research program.

	3-D Enhanced Geometry	2-D Enhanced Geometry	Plain Surface Geometry
R-410A	2 surfaces required	none required	none required
R-507A	1 surface required	1 surface required	none required
R-22	1 surface required	1 surface required	1 surface required

A two-dimensional (2-D) enhanced geometry refers to an integral-fin design. A three-dimensional (3-D) geometry refers to a nucleate boiling surface -- the surface geometry is three-dimensional.

The actual oil concentration in the test section may or may not vary from row to row depending upon test conditions. Preference will be given to those investigators intending to evaluate the effects of row depth upon both local oil concentration and heat transfer coefficient in addition to measuring the overall bundle performance.

Several oil concentrations shall be evaluated in order to establish performance trends. It is desirable for the range oil concentration evaluated to go as high as 10%; concentration defined here as the value in the test section determined from sampling. Note, since the small experimental bundle will be operating with refrigerant liquid and oil leaving the top of the tube bundle during oil effects work, any concentration evaluated essentially requires the oil to be introduced continuously (inlet concentration equal to concentration in test section) at the inlet of the evaporator to achieve a steady state oil concentration in the test section.

The oil(s) used in the proposed investigation will be recommended by the PMS. Oil effects work will be conducted with R-410A and R-507A. Those investigators willing to evaluate more than one oil with either refrigerant in order to ascertain viscosity effects will be given preference. In addition, pure refrigerant testing shall be conducted with R-22 so that baseline performance for the test facility may be established. Oil effects work with R-22 is not required.

The author of this work statement perceives that proposals may be generated with any of three different approaches for the oil effects work:

- perform oil effects work using a pool boiling condition (no liquid refrigerant exiting the top of the test section), but incorporate overfeed for pure refrigerant work to achieve a range of inlet and outlet qualities (LEAST DESIRABLE APPROACH)
- perform low oil concentration (perhaps less than 5%) work with overfeed, but resort to a pool boiling condition to achieve oil concentrations between 5% and 10% (MORE DESIRABLE)
- evaluate oil concentrations as high as 10% using overfeed to achieve requested mass flux/quality range (IDEAL)

Those investigators with facilities only capable of operating the experimental tube bundle in an overfeed condition during pure refrigerant testing should clearly state this fact in the proposal, because such a limitation implies that all oil effects work will be performed using a “flooded evaporator” test condition -- no liquid refrigerant or oil leaving the top of the tube bundle -- which is not the intent of the program.

Although only one saturation temperature is required, evaluation of additional temperatures to establish the effects of refrigerant properties upon heat transfer performance is deemed desirable for the purpose of correlating data generated in this study. Those investigators intending to provide additional temperature effects work should state this objective in the proposal.

Task III - Reporting of Data

The results of this research project must be reported as described below in "DELIVERABLES". A schedule for estimating the time to completion shall be developed by the contractor and kept up to date throughout the work for the benefit of the committee.

DELIVERABLES

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

b. The Principal Investigator shall report in person to the TC at the annual and winter meetings, and answer such questions regarding the research as may arise.

c. A Final Report shall be prepared and submitted to the Manager of Research by the end of the contract period covering complete details of all research carried out on the project. The final report should include:

   - Uncertainty Analysis
   - Literature Search
   - Non-dimensional correlations for pressure drop and heat transfer
   - Experimental Data in tabular form

   Unless otherwise specified, six draft copies of the final report shall be furnished for review by the Project Monitoring Subcommittee (PMS).

   Following approval by the PMS and the TC/TG, final copies of the final report will be furnished as follows:

   - An Executive Summary suitable for wide distribution to the industry and to the public.
   - Six bound copies.
   - One unbound copy, printed on one side only, suitable for reproduction.
   - Two copies on 3-1/2 inch diskette(s); one in ASCII format and one in Microsoft Word 6.0.

d. If the primary result of this project is a design guide, manual, guideline, etc., these terms may be substituted for "final report" in (c) above.

e. One or more Technical Paper(s) shall be submitted in a form suitable for presentation at a Society meeting. The Paper(s) shall conform to the Society's "Submitting Manuscripts for ASHRAE Transactions" which may be obtained from the Special Publications Section.

f. All papers or articles submitted for inclusion in any ASHRAE publication shall be made through the Manager of Research and not to the publication's editor.

g. A Technical Article suitable for publication in the ASHRAE Journal may be requested by the Society or the PMS.

LEVEL OF EFFORT

It is expected that Tasks I through III, shown above, will take thirty (30) months to complete. Six (6) person-months of the Principal Investigator and thirty (30) person-months of the research assistant are estimated. A total cost of $155,000 is anticipated.

OTHER INFORMATION FOR BIDDERS

Those bidding on this project should have extensive experience with boiling heat transfer, two-phase flow, and fluid mechanics.

Suggested Approach

a. Review the RP-392 Final Report or resulting technical articles with respect to test facility description and experimental methods. The facility used in RP-392 for the most part satisfies experimental requirements of the current project, with the exception of (1) lack of oil management system and (2) lack of refrigerant mixture composition sampling system. Semi-empirical models generated in RP-392 are state-of-the-art and should be reviewed thoroughly. Where appropriate, data from RP-392 should be taken into account for the generation of semi-empirical and/or analytical heat transfer correlations in the proposed research program.

b. When available, review the RP-751 Final Report with respect to literature survey, experimental methods, and results. This study will be completed in 1998, so its literature survey is fairly recent. Where appropriate, data from RP-751 should be taken into account for the generation of semi-empirical and/or analytical heat transfer correlations in the proposed research program.

c. It should be noted that both RP-392 and RP-751 were performed using surface temperature measurements in the tube bundle as opposed to some form of LMTD analysis. Liquid to refrigerant heat transfer and associated LMTD analysis is preferred for the proposed research program. However, proposals may be submitted that rely upon the surface temperature approach for data reduction, although they will receive lower priority.

d. R-410A is considered a high pressure refrigerant, so test facility construction must be designed for all conditions foreseen in operation. Strength and materials compatibility for refrigerant/oil mixtures must be considered in facility design.

e. A relatively large chiller system will be required to serve as the heat sink for the experimental test facility. Carefully review the range of qualities, heat fluxes, and mass fluxes requested by this work statement. Of course the proposed bundle size also heavily impacts required heat sink capacity. Many academic laboratories do not have hardware in place to meet the requirements of this research program. The chiller system (or equivalent) proposed for this work must be clearly described in the proposal.

PROPOSALS

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

a. Background and literature review.

b. Statements describing test facilities, equipment, capabilities including uncertainties, procedures, correlation methods, etc., to be used.

c. Statements indicating experience in conducting research related to boiling heat transfer, two-phase flow, and fluid mechanics.

d. Resume of the Principal Investigator and other key personnel involved in the study.

e. Planned schedule and length of time for the project to be completed.

f. Budget information.

REFERENCES

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Webb, R.L. and McQuade, W.F. 1993. Pool Boiling of R-11 and R123 Oil-Refrigerant Mixtures on Plain and Enhanced Tube Geometries. ASHRAE Transactions, Volume 99, Part 1, pp. 1225-1236.

Note: ASHRAE research project final reports 392 and 751 (751 - when available) may be obtained by contacting

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