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Refrigerants & Energy Efficiency

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REFRIGERANTS & ENERGY EFFICIENCY

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ABSTRACT

Environmental concerns (i.e., ozone depletion and greenhouse warming) are forcing major shifts from traditional choices of refrigerant working fluids for individual systems and for specific applications. Energy efficiency has taken on new urgency to mitigate fossil fuel demands and associated greenhouse impacts while allowing for future growth of refrigeration demand.

Energy effectiveness has thus become an increasingly important parameter and a key focus in the refrigerant selection process. Efforts to generically rank refrigerants with respect to their inherent thermodynamic efficiencies have thus far not proven to be very productive. Much conflicting information has surfaced as to the true impacts on energy demand of various candidate fluids.

It is apparent that much more than a simple thermodynamic cycle efficiency is involved. Other factors may have equal or even greater impact on the ultimate energy demands associated with any particular working fluid and/or system design. Even calorimeter testing may prove misleading in the absence of appropriate optimization.

INTRODUCTION

The relationship between refrigerant choice and future energy demands is a legitimate concern. As we approach the 21st century with a heightened sense of urgency to achieve crucial environmental goals, established patterns of refrigerant use are in a state of flux. Concerns over stratospheric ozone and atmospheric "greenhouse" warming are forcing fundamental shifts and reappraisals of refrigerant choices for virtually every sector of the refrigeration and air conditioning industries. As traditional CFC working fluids are phased down and replaced by less familiar alternatives which minimize or eliminate potential ozone damage, it is important to limit any negative impacts on energy efficiency which could increase consumption of fossil fuel based energy with attendant greenhouse warming. Ideally, future systems should provide energy efficiencies which are comparable to or better than their predecessors. This is typically easier said than done. The refrigerant is, of course, a key ingredient in achieving favorable energy efficiency. It is important, though, to acknowledge that the refrigerant is only one of a number of variables with potential to affect the ultimate energy demand of any real system. Furthermore, the contribution of the working fluid is only partially traceable to its thermodynamic properties. Other attributes can be equally significant. The interrelationships and mechanisms involved are more complex than is commonly recognized.

Misperceptions and confusion have resulted from attempts to ascribe relative rankings on a generic basis to different fluid candidates based away from limited data whether these be individual machine tests or elementary thermodynamic cycle calculations. In truth, the "COP" or energy efficiency is not an inherent fluid property in the way that vapor pressure or densities may be. Actual system Coefficients Of Performance reflect the cumulative impacts of many factors. These include (but are not limited to) thermodynamic properties, heat transfer characteristics, pressure drop characteristics, the degree of optimization of compressors, heat exchangers, and other system components, lubricant behavior, etc.

For real systems, the actually realized COPs vary considerably from the ideal COPs calculated from simplified and standardized cycle calculations. Inefficiencies throughout the system inevitably take their toll reducing the final COP to some fraction of the ideal theoretical value. Typically, these system-related inefficiencies account for most of the deterioration from ideal to actual. These system related losses are not the same though for all fluids and/or cycle conditions.

System optimization is the process through which the system components and the cycle itself is fine-tuned to minimize these losses individually and collectively. Because of the differences from one fluid to another, thermodynamic or otherwise, significant differences in component sizing, design and arrangement may emerge as the optimization process proceeds for one fluid vis a vis another. Ultimately, the load on the power utility's lines is dependent on the COP of the total system. This does not necessarily correlate with the theoretical cycle COPs calculated for individual fluids.

SOURCES OF INEFFICIENCY

J. L. Schulze, in his paper, "Room Air Conditioner Efficiency - Potentials and Limitations", presented at the 1974 Purdue Conference on Improving Energy Efficiency in HVAC Systems and Components[1] employed graphic methods to visualize COP degradation. Fig. 1 here is a redrawing of his Figure 6. The EER (energy efficiency ratio) terminology utilized in Schulze's paper has been converted to COP terminology. The example represents a room air conditioner working between a source temperature of 80°F (the cooled space) and a sink at 95°F (outside ambient). It illustrates a deterioration of COP from the theoretical limit (Carnot cycle) of 36.0 to an actual achieved COP of only 1.76 for an overall system efficiency of only about 5% relative to Carnot.

Major COP deterioration occurs in the heat transfer processes which were only 13% efficient in this case accounting for 91% of the total degradation. The motor-compressor at 52% efficiency accounted for another 5% of the total. The real cycle efficiency of the fluid at 78% of Carnot (based on 130° Cond. and 40° Evap.) accounted for 3% of the total. The remaining losses (less than 1%) were attributed to miscellaneous items such as piping, controls, insulation, etc.

The above example based on a hypothetical system representing one class of equipment of mid-70's vintage is obviously not representative of today's universe of refrigeration technology. Nevertheless, it can be useful in providing a methodology and frame of reference for evaluating the relative impacts of subsystems on overall energy efficiency. The small lift (Carnot) between source and sink in this example contributes to the very high (percentage wise) degradation of Carnot in the heat exchange processes. At greater thermal lifts the theoretical Carnot efficiency declines rapidly. The inefficiencies (as a percentage) imposed by ΔT requirements at heat exchangers are thereby lessened.

It should also be noted that other considerations may govern the selection of working fluid temperatures. In the air conditioner, for example, dehumidification is an important consideration. Accordingly refrigerant evaporating temperature is selected to provide heat exchanger surfaces below the dew point of the ambient air. In any event, heat transfer constitutes a primary barrier to achieving Carnot cycle efficiencies.

The above example showed that the heat transfer processes and the motor compressor inefficiencies present the greatest potential for COP improvement. A significant observation, here is the relatively small contribution to COP degradation attributable to thermodynamic inefficiencies of the refrigerant. Examination of tabulations of calculated theoretical COP's of various refrigerants such as that appearing in Table 1 indicate only slight difference in theoretical COP's amongst refrigerants with similar boiling points. One might thus conclude that the impact on overall system COP of switching refrigerants between candidates of similar boiling points should be relatively small. Real life experience tends to support this conclusion <u>based on optimized systems.</u> In the absence of such optimization major deviations can occur. These are typically reflective of indirect system impacts (other than thermodynamic cycle efficiency).

<u>THERMODYNAMIC FACTORS</u>

Table 1 compares four refrigerant fluids for an air conditioner cycle similar to that cited in the Schulze paper. Thermodynamic data sources are noted in references 2, 3 and 4. Table 2 compares the same four fluids operating on a low temperature cycle. While absolute COP values are lower for this cycle the percentage realization of Carnot remains similar. Also, the relative ranking amongst these fluids remains the same --- R-12 appears to be the most energy efficient -- R-22 the least. This runs counter to industry experience in small to intermediate systems where R-22 performance has typically been found to be as good or better than that of R-12.

In Tables 3 & 4 theoretical COP's have been calculated for different assumed levels of superheat and subcooling. These assume utilization of the cooling potential during superheating and subcooling. Inspection of these data reveal different relative sensitivities amongst these fluids.

All of the candidates show significant benefits from liquid subcooling. The impact of suction superheat is less and more variable. Subcooling has no impact on compressor work and will always increase the cooling effect unless the energy to provide the subcooling is provided at the expense of the cooling effect. Subcooling will thus increase the COP of the system. Superheat, on the other hand, increases the compressor work (per lb. of circulating refrigerant) assuming no change in isentropic efficiency. Suction superheating simultaneously results in some vapor density reduction thereby reducing mass flow through a given displacement compressor tending to reduce the power consumption. The net effect on COP may be either positive or negative depending on the fluid. Additionally the source of the superheat affects the net result. Where the energy to provide the superheat contributes to the cooling effect the COP is most likely to benefit. On the other hand superheating which does not provide such a contribution inevitably penalizes the COP.

In an hermetic motor superheating occurs as a consequence of heat removal from the windings. The utility of this function cannot be denied but thermodynamically this contributes nothing to the useful cooling effect and thus exacts a price in terms of the COP.

Referring again to Tables 3 and 4, for R-22 the net effect of useful superheating on the COP appears to be negative. W.D. Cooper examined this issue [5] and noted an anomaly in that actual calorimeter tests with R-22 showed a positive COP benefit from suction superheating. He analyzed several hypotheses and concluded that the major reason was that in the absence of purposeful utilization of superheat, that unintended and non-useful superheat which occurred internally in the compressor prior to the suction valves tended to penalize the low superheat option to a greater degree than if some utilization were made of the cooling effect prior to entering the compressor shell. The above illustrates the difficulty in translating from thermodynamic data alone to real-world performance.

OTHER FACTORS

Heat transfer effectiveness, pressure-drop losses and differences in motor-compressor efficiencies can all contribute to the relative inefficiency of any system with alternate refrigerant options. At first glance, the impacts of refrigerant substitution on heat transfer might seem to be insignificant where the primary barrier to heat transfer is on the air side. In actuality significant penalties can occur where such substitution neglects optimization. Even where loadings are similar, differences in flow rates, pressure drops, etc. can inhibit the overall effectiveness of any specific coil thereby increasing the thermodynamic lift imposed on the compressor.

Conversely, a fluid with superior heat transfer and pressure drop characteristics may enjoy a thermodynamic lift advantage in an appropriately optimized system and can provide an actual COP advantage even where its thermodynamic properties might suggest a penalty. The system lubricant may also impact the COP if it affects either the heat transfer or pressure drop performance of the system. An inappropriate lubricant selection could obscure otherwise favorable refrigerant performance. In the usual case where the refrigerant and lubricant exhibit mutual solubility, there are subtle impacts on the thermodynamic properties. These are usually small and difficult to accurately evaluate and are typically ignored in theoretical calculations.

The motor-compressor simultaneously represents a major source

The motor-compressor simultaneously represents a major source of system inefficiency and also a source of uncertainty in evaluating relative efficiencies of working fluids. Differences in mass flow-rates, specific-heats, pressure-drops, etc. can either benefit or exacerbate internal heat transfer losses, valve losses, and ultimate mechanical efficiencies. Furthermore, differences in volume flow requirements per ton can affect both the mechanical and electrical efficiency of the unit. Where cooling capacity is maximized, mechanical efficiency also tends to peak since fixed frictional losses are then distributed over a larger delivered capacity. This is true so long as the incremental capacity is achieved with minimal impact on valve flow losses, etc. At some point, these will limit further capacity (and COP) gains.

In the case of hermetic motor compressors, the motor and compressor are typically matched to maximize overall efficiency at the predominant loading. Motor loadings above or below the design point will lower the electrical efficiency of the motor. One consequence of this is that the optimum match for one refrigerant is unlikely to remain optimum for a different refrigerant operating in the same compressor.

Valve port sizes, valve spring characteristics, internal heat transfer, cylinder clearances and myriad other details of a particular compressor design may favor or penalize the relative performance with different working fluids. Ideally, comparative testing of refrigerant fluids should be conducted in compressors optimized for each. This is rarely practical or possible. Lacking that luxury one should resist the temptation to interpret individual test results broadly and generically. It is sometimes illuminating to conduct similar tests in a range of compressors to observe how much of the difference between fluid candidates is compressor-specific.

CONCLUSION

This paper has not provided any simple answers. That was not its mission. Instead the message here is that one ought to be skeptical when over-simplistic comparisons are made of the relative impacts of alternate fluids on energy efficiency. The COP or efficiency is not an inherent property of a fluid. Fluids with similar vapor pressure characteristics are likely to provide comparable energy efficiency provided that the system and its individual components are appropriately optimized. The optimization process may not be simple or even well defined but does go on inexorably over time as practical experience is accumulated, as systems evolve and as improvements are achieved.

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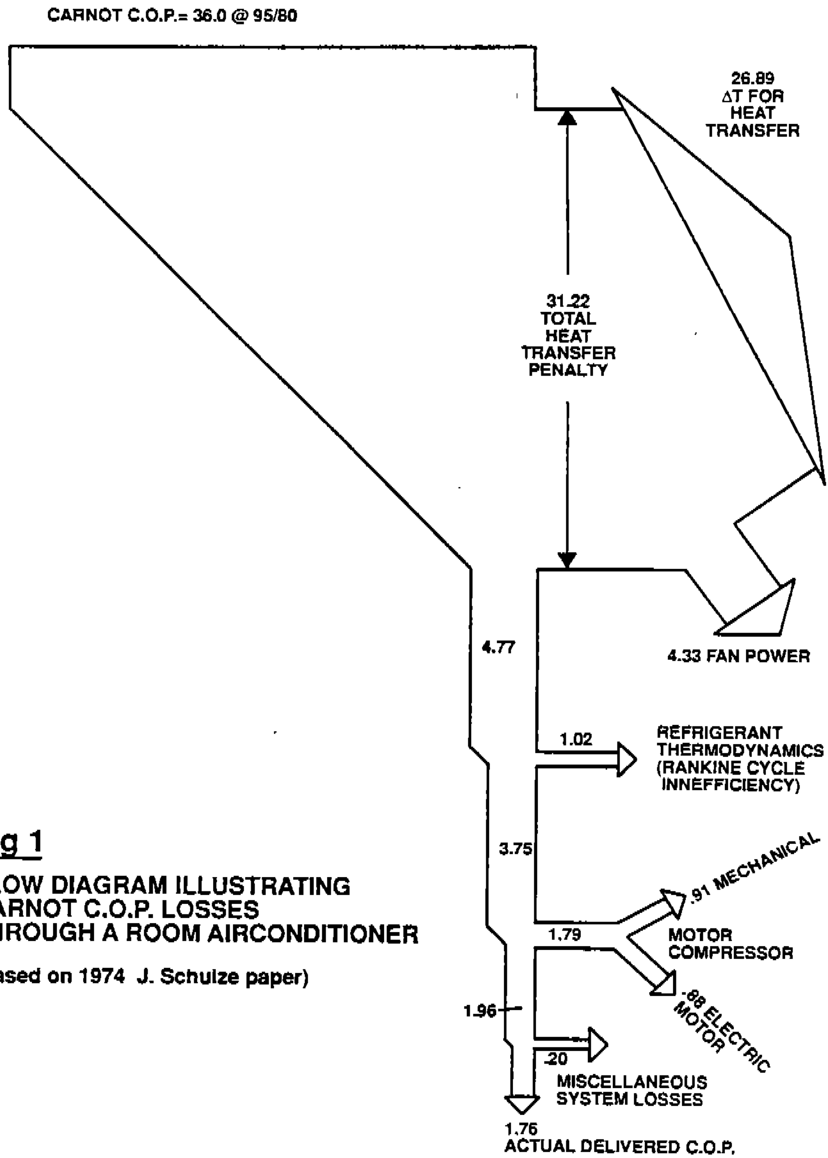

Fig 1

FLOW DIAGRAM ILLUSTRATING CARNOT C.O.P. LOSSES THROUGH A ROOM AIRCONDITIONER

(Based on 1974 J. Schulze paper)

TABLE 1

REFRIGERANT PERFORMANCE (THEORETICAL)

Based on 40°(F) EVAP., 130° COND. WITH 65° SUCTION & 10° SUBCOOLING

	R-134a	R-12	R-500	R-22
Cond. Press. (Psia)	213.5	195.7	231.7	311.5
Evap. Press (Psia)	49.8	51.7	60.7	83.2
Disch. Temp (°F)	160	164	168	193
Mass Flow/Ton (#/min)	3.255	4.066	3.394	3.000
Comp. Displacement/ Ton (CFM)	3.308	3.366	2.886	2.120
Relative Capac.	100%	98%	115%	156%
COP	4.40	4.55	4.49	4.36
% of Carnot	79%	82%	81%	78%

TABLE 2

REFRIGERANT PERFORMANCE (THEORETICAL)

Based on 10°(F) EVAP., 100° COND. WITH 20° SUCTION & 10° SUBCOOLING

	R-134a	R-12	R-500	R-22
Cond. Press. (Psia)	138.9	131.9	155.8	210.6
Evap. Press (Psia)	16.69	19.19	22.51	31.16
Disch. Temp (°F)	144	151	155	190
Mass Flow/Ton (#/min)	3.057	3.893	3.196	2.784
Comp. Displacement/ Ton (CFM)	8.887	8.246	7.032	5.064
Relative Capac.	100%	108%	126%	175%
COP	3.20	3.28	3.25	3.17
% of Carnot	78%	80%	79%	77%

TABLE 3

COPs WITH SUPERHEATING AND/OR SUBCOOLING

40° EVAP/130°COND

	R-134a	R-12	R-500	R-22
Satd. Cycle	4.05	4.27	4.20	4.16
% of Carnot	(73)	(77)	(76)	(75)
65° SUCT/0° Subcool	4.14	4.32	4.25	4.14
% of Carnot	(75)	(78)	(77)	(75)
Sat. Suct./10° Subcool	4.33	4.52	4.46	4.39
% of Carnot	(78)	(81)	(80)	(79)
65° Suct/10° Subcool	4.40	4.55	4.49	4.36
% of Carnot	(79)	(82)	(81)	(78)

TABLE 4

COPs WITH SUPERHEATING AND/OR SUBCOOLING

-10° EVAP/100°COND

	R-134a	R-12	R-500	R-22
Satd. Cycle	2.97	3.09	3.07	3.06
% of Carnot	(73)	(76)	(75)	(75)
20° SUCT/0° Subcool	3.03	3.13	3.10	3.04
% of Carnot	(74)	(77)	(76)	(74)
Sat. Suct./10° Subcool	3.15	3.25	3.24	3.21
% of Carnot	(77)	(79)	(79)	(78)
20° Suct/10° Subcool	3.20	3.28	3.25	3.17
% of Carnot	(78)	(80)	(79)	(77)