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ABSTRACT

Many researchers have believed and claimed that the application of non-azeotropic refrigerants would increase air conditioning or heat pump cycle efficiency. Some of them have carried out experiments in order to confirm their belief, and especially to provide an approach to air conditioner or heat pump design for improving cycle efficiency by using non-azeotropic refrigerants. However, even though there are some successful claims, the real benefits have not materialized in the air-cooled commercial products. The question is why?

Air conditioning and refrigeration machines can be divided into two types. One is water-cooled machines and the other is air-cooled machines. The literature and some commercial products have shown that the efficiency of a water-cooled machine is improved by a non-azeotropic refrigerant cycle as compared to a pure or azeotropic refrigerant cycle. However, the results for the air-cooled machines are mixed. A close examination of the claims of success for the air-cooled machines suggests some problems with their results. The most common problem is defining the base line for comparison. Therefore, those claims may not do fair comparisons.

The basic question goes back to the fundamental cycle analysis. The water source and indoor air are normally limited and thus it represents a finite heat source or sink. The out-door air is unlimited and it represents an infinite heat source or sink. For an infinite heat source or sink theoretically the temperature of the source or sink does not have to increase or decrease. Practically, the temperature change can be very small. For an infinite heat source or sink, the temperature glide associated with non-azeotropic refrigerants does not represent a benefit but a deterioration of cycle efficiency.

Therefore, a non-azeotropic refrigerant provides benefits for water-cooled machine which have a finite heat source or sink. Those benefits would be reduced or even disappear for air-cooled machines due the outdoor air as an infinite heat source or sink.

INTRODUCTION

The concept of using a non-azeotropic refrigerant mixture can be traced back to the U.S. patent issued to Ashley *et al.* (1949). The patent claimed that a refrigerant mixture with temperature glide would offer a process that "involves no irreversible loss of thermal head since the vapor and the corresponding liquid phase are at each point in contact. There is a progressive interchange of the two components between the vapor and liquid phase which proceeds apace with the condensing action to maintain the vapor and liquid in equilibrium." After the patent, many researchers have tried to prove the claim of energy efficiency associated with non-azeotropic refrigerant mixtures and practitioners have tried to put it in work.

McHarness and Chapman (1962) provided the capacity and performance data for several different combinations of refrigerant mixtures. The experiments were conducted on a calorimeter test unit. The condenser was a tube-in-tube water cooled, counterflow unit made up of copper tubing with brass headers. The evaporator was heated by using variable voltage controllers on four 1000-watt heaters. They found that the use of mixtures provided almost unlimited possibilities for varying the capacity of refrigerating systems. However, they did not report a significant improvement in efficiency.

Cooper and Borchardt (1979) conducted experiments with three different mixture compositions on a calorimeter system. They reported that *air-to-air* heat pumps could benefit from the use of non-azeotropic refrigerant mixtures as a means of increasing capacity at low outdoor ambient over a single-component fluid. A 60% improvement in compressor capacity was realized, but no efficiency improvement was reported.

Vakil and Flock obtained U.S. patents (1979, 1980) and claimed "a method of modulating the capacity of a vapor compression cycle device which comprises compressing a multi-component working fluid mixture." Since then, many research results have reported that the capacity can be modulated by using Non-azeotropic refrigerant mixtures.

Schulz (1985) focused on the general behavior of refrigerant mixtures, the characterization of such behavior, and the effects on system performance and operating conditions. Based on these characteristics, he suggested some system designs which took advantage of mixed refrigerants, such as temperature glide.

Kauffeld *et al.*(1988) studied an experimental heat pump with counter-flow *water-to-refrigerant mixture* heat exchangers which demonstrated an increase in the coefficient of performance of up to 32% for an optimized mixed refrigerant as compared to the performance with pure R-22. Such a significant increase in performance might be attributed to a favorable composition of the refrigerants, low temperature lift of the working fluid and counter-flow heat exchangers.

Chwalowski (1991) pointed out that for all examined experimental results of residential heat pumps with *air-to-refrigerant* heat excahange, where mixtures were used, the improvement was only 0%-11% for either the heating or the cooling mode, while theoretical considerations suggested an improvement of between 35% to 50%.

Chen *et al.* (1992) reported that "a power saving of better than 20%, compared to a unit running on pure R-22, was achieved. A power saving of 25% by use of mixtures is considered a realistic goal." The test employed a two-section evaporator and the refrigerant mixture used was R22/R142b. The test results were compared to that computed for a standard unit running on pure R-22 with the same heat transfer surface.

Bensafi and Haselden (1993) incorporated the test results by Chen *el al.* (1992) in a computer model by which the performance of a similar system running on a wide range of mixtures is simulated. They predicted that for a range of mixtures, from binary to quaternary, a unit could be designed with a 25% power saving for an additional first cost of the same order.

Those results in the literature seem to be inconsistent regarding the benefits of non-azeotropic refrigerants. However, if we sort them out, then the inconsistency is superficial. The results can be divided into two categories, one from experiments and the other from simulations. The experimental results can be further divided into two sub-categories, water-cooled machines and air-cooled machines. The experiments using water-cooled machines show encouraging results, while air-cooled machines do not. This discrepancy would be expected if the difference between water-cooling and air-cooling has been considered. This will be discussed in the following section. Because some of the reported simulations do not make distinctions between water-cooled and air-cooled machines, the conclusions from those simulations could be misleading by over-estimating the benefits of non-azeotropic refrigerants. The baseline used in the Chen's (1992) and Bensafi's (1993) reports are questionable. The optimization of heat exchanger design depends on whether the heat source or sink is finite or infinite and depends on the temperature glide of refrigerants too. Their results did not demonstrate that their heat exchangers had been optimized both for R-22. Therefore, the comparison cannot be generalized.

TWO DIFFERENT HEAT SOURCES

In thermodynamics, a heat source (a heat sink can be treated as a negative heat source) could be finite or infinite. The temperature of a finite heat source would increase or decrease when the source releases or absorbs heat, while the temperature of an infinite heat source would not change due to the assumption that the total heat capacity of the source is infinite. Of course, the assumption is only an approximation. Even though the common heat sources have only finite heat capacity, they can be so huge, compared to an air-conditioning system, that an infinite heat source is good approximation. An example is outdoor air.

For an air-conditioning system, heat is normally absorbed from air or from water, and rejected into the air or water. A water source is normally finite, except putting heat exchangers directly into oceans, or rivers, or big wells, which is normally not the case. The water enters the system with a certain flow rate and its temperature increases or decreases by absorbing or rejecting heat. Therefore, a water source is a finite heat source. An air-conditioning system processes a certain amount of indoor air per unit time by absorbing the heat from the air stream and the temperature of indoor air is then reduced to a specified level. Thus, the indoor air is a finite source too. The outdoor air seems to be the same as indoor air, but it is fundamentally different. First, the supply of the outdoor air is unlimited. In principle, we can use as much outdoor air as we want. Second, the temperature of the outdoor air stream can remain about the same after absorbing heat. One counter argument is that, even though the outdoor air is infinite, the outdoor air stream entering a system is finite. The key is that the flow rate of outdoor air stream is unlimited such that the temperature change of the stream can be minimal. For example the outdoor air can pass through a single row heat exchanger and then leave the system. The temperature change of the stream can be controlled to be very small by forcing a high flow rate through the heat exchanger. Because the stream leaves the system after the single row, its temperature change has no further effect on the system. In such a case, the outdoor air is close to an infinite heat source. The above discussion can be summarized in Table 1.

Table 1. Type of heat sources

Heat source (or sink)	Source type
water	finite
indoor air	finite
outdoor air	infinite

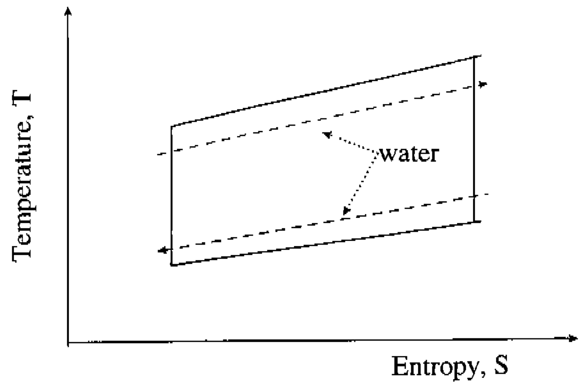

Figure 1. T-S diagram for water-cooled machine with non-azeotropic refrigerant

Once we realize the difference between the two types of heat sources, the different impact of non-azeotropic refrigerant on different systems is expected.

WATER-COOLED AND AIR-COOLED MACHINES

A water-cooled system is defined as an air-conditioning system using water as both the heat source and sink. For such a system, the temperature of heat source and sink changes in passing through the heat exchanger (as shown in Figure 1). If the temperature glide of a non-azeotropic refrigerant matches the temperature change of the water, then the work input to the system can be reduced and the efficiency of the cycle is improved.

Nonetheless, for an air-cooled system, the situation is quite different because the outdoor air behaves as an infinite heat sink. The temperature of the outdoor air can remain about the same as explained in the previous section. The temperature of indoor air, as a finite heat source, has to decrease as it passes through heat exchanger (Figure 2). If the temperature glide of a non-azeotropic refrigerant can match the temperature change of the indoor air, it certainly will mismatch the temperature of the outdoor air. The benefit gained from the indoor heat transfer is canceled by the disadvantage on the outdoor heat transfer.

A pure refrigerant (Figure 3) has an advantage in out door heat transfer, but a disadvantage in indoor heat transfer. Compared to a pure refrigerant, a non-azeotropic refrigerant shows a benefit for water-coole machine, but does not show definite advantages for air-cooled machine.

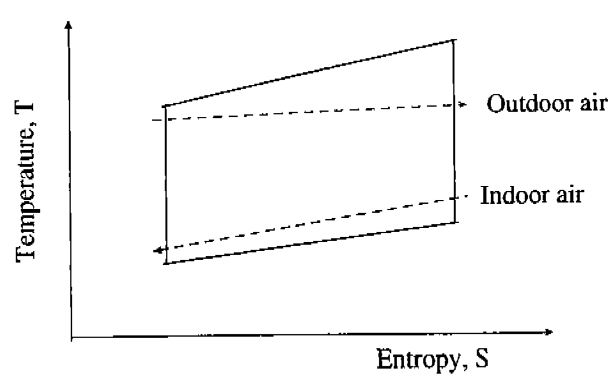

Figure 1. T-S diagram for air-cooled machine with non-azeotropic refrigerant

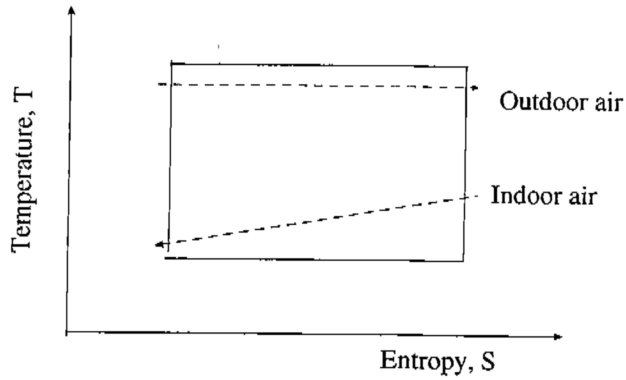

Figure 3. T-S diagram for air-cooled machine with pure or azeotropic refrigerant

Based on the above discussion, we can specify what characteristics an ideal refrigerant should have. For example, for a heat pump that heats air directly, an ideal refrigerant should have a temperature glide in the condenser and no or a minimal temperature glide in the evaporator (Figure 4). Such a refrigerant would minimize the work requirement for the system and provide mazimum system efficiency. It seems that it is unrealistic to look for such refrigerant. However, refrigerant CO_2 which passes through condenser at above super-critical condition and evaporates in a two-phase region provides characteristics quite similar to the ideal case. This is part of the reason that CO_2 shows promising efficiency in heating cycles. It is also no surprise that its performance is quite poor for cooling cycles, in which its temperature change mismatches both in condenser and evaporator.

CONCLUSIONS

Water and indoor air can be characterized as finite heat sources or sinks, while outdoor air can be characterized as an infinite heat source or sink. The temperature glide of non-azeotropic refrigerants benefits a finite heat source or sink by matching the temperature change of the water or air streams passing through a heat exchanger. On the other hand, a non-azeotropic refrigerant pays a penalty for an infinite heat source or sink. As a result, non-azeotropic refrigerant can improve the efficiency of a water-cooled machine, compared to a pure refrigerant. Such improvement should not be expected for an air-cooled machine because the outdoor air acts as an infinite heat source or sink and the temperature glide of a non-azeotropic refrigerant mismatches the outdoor temperature.

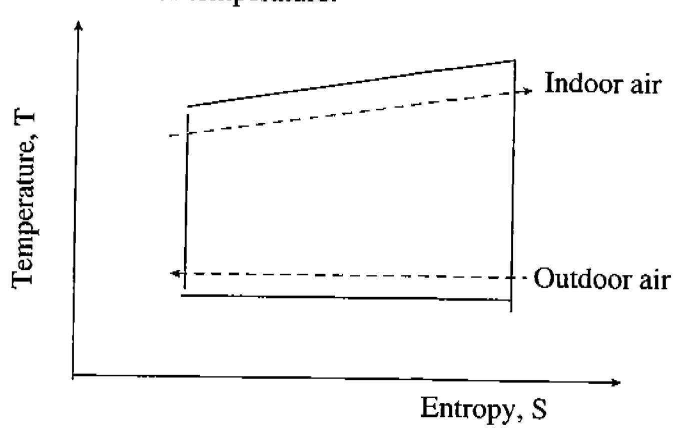

Figure 4. T-S diagram for air-cooled machine with ideal refrigerant

The ideal refrigerant for an air-cooled machine can be characterized as having temperature glide for the indoor stream and have no or a minimal temperature glide for the outdoor stream.

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