

Cooling System Selection for Arid Zones Using Fuzzy Sets

A.F. Abdul-Fath and H. Sofrata

*Department of Electrical Engineering and Department of
Mechanical Engineering,
College of Engineering, King Saud University, Riyadh, Saudi Arabia.*

ABSTRACT. Selection of cooling systems based upon the traditional definition of the coefficient of performance (COP) may create misleading results because it does not consider all factors affecting the selection. A multi-attribute decision analysis is necessary to differentiate between various air conditioning cooling systems for arid zones. The Kingdom of Saudi Arabia is chosen to be the case study and seven main criteria, which include twenty subcriteria are selected.

To carry out such analysis, an Interactive Fuzzy Decision Analysis Computer Package (IFDA) is used. This package utilizes verbal rating, weights for each attribute and subattribute as Input. IFDA is based on Fuzzy Set theory. The results show that the Li Br absorption dual system is the best air conditioning cooling system to be used in Saudi Arabia and the ammonia water absorption system is the second best.

1. Introduction

The traditional definition of the coefficient of performance (COP) of a refrigeration cycle is the ratio of the heat absorbed (from the space to be cooled) to the necessary compressor work. Selection of a cooling system based upon this definition may create misleading results because it does not identify the heat input base. For example, for an internal combustion engine driven vapor compression system (ICEDVC), the COP is about 0.8 (Whitlow 1966), while for the cooling system, which is electrically driven, the COP is about 2.5. If the heat input base is considered on the same bases, the two COP values should be approximately the same. On the other hand, if the running cost is considered, a refrigerating machine driven by an ICEDVC will be lower in cost than electrically driven machine. This means that the running cost of the electric driven refrigerating machine is generally

higher. However, the electrically driven system is more reliable than other systems. Finally, the capital cost must also be accounted for in the selection process, because it has a considerable weight regarding a system's selection. In addition, the COP definition does not consider other important factors which may affect the system selection. Therefore, the use of a multi-attribute decision analysis scheme is necessary to differentiate between various air conditioning cooling systems.

The systems evaluated here are: the electric motor driven vapor compression (EMDVC), the internal combustion engines driven compression (ICEDVC), NH_3 absorption system (NH_3A), Li Br absorption simple system (Li Br AS), and Li Br absorption dual system (Li Br AD) (see Sofrata *et al.* 1979, 1980, Sofrata and Abdul-Fattah 1981, 1982). This analysis will consider not only the COP but also factors; such as condenser cooling, cooling tower, maintenance, running cost, spare parts, design, installation, and other factors which cannot be measured easily in terms of energy or money.

The multi-attribute fuzzy set decision theory which is well defined and developed (see for example Bass and Kwakernaak 1977, Bellman and Giertz 1973, Capocelli and De luca 1973, Chang 1972, Graines 1976 a,b, Kenarangui *et al.* 1980, Watson *et al.* 1979 and Zadeh 1965, 1972, 1976) is found to be the most suitable for the air conditioning cooling systems selection in Saudi Arabia. This is because, with the help of this theory, one can verbally rate each alternative with respect to each criterion alone, independent of all other alternatives. In the references list some importante works are given.

2. The Selected Cooling and Refrigerating Systems

In this section, the selected cooling and refrigerating systems will be very briefly reviewed not only to acquaint the reader, but also to define the main components of these systems.

2.1. Vapor Compression Cooling System

A schematic of a vapor compression cooling system is shown in Figure 1. Such refrigeration system is the heart of any air conditioning system. The system cools the return air and supply it to the space to be air conditioned.

In such system the condenser may be cooled using cooling water, which is provided from a cooling tower. In the Kingdom of Saudi Arabia, cooling towers may not be considered as a desirable solution because of water shortage in the country. Another alternative for cooling the condenser is air cooling. Air cooled condensers are widely used, but this will decrease the coefficient of performance and creates some accoustics problems.

In the evaporator, the refrigerant will evaporate, and the return air may be cooled directly by flowing over the evaporator. A cooling medium, brine, may also

be used, where the air handling units are introduced to bring the space air to the cooled medium. The compressor sucks the evaporated refrigerant (1) and compresses it to the condenser pressure (2). The compressor may be driven by using different prime-movers such as internal combustion engines or electric motors.

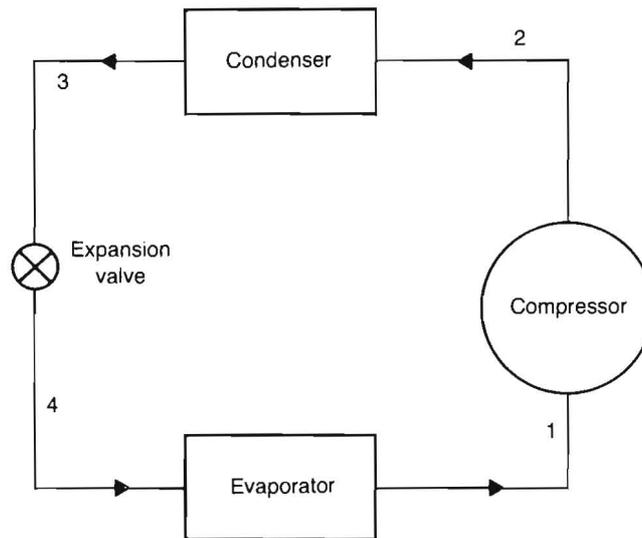


Fig. 1. Vapor compression cooling system.

The condensed refrigerant is throttled through the expansion valve (3), where the pressure and the temperature will be reduced and the cooling effect is carried out in the evaporator (4).

2.2. Electric Motor Driven Vapor Compression Cooling System (EMDVC):

Figure 2 shows a vapor compression refrigeration unit driven by an electric motor. This represents an open type system, in which the compressor and the electric motor are not in an enclosure. Hence, a seal must be used on the shaft penetration through the compressor housing in order to prevent refrigerant high pressure gas from leaking out or air from leaking if the suction pressure in the crankcase is lower than atmospheric.

To avoid leakage at the seal; at one hand, and minimize the cost on the other hand, the electric motor and the compressor are often enclosed in the same housing. This type is known as hermetically sealed compressors.

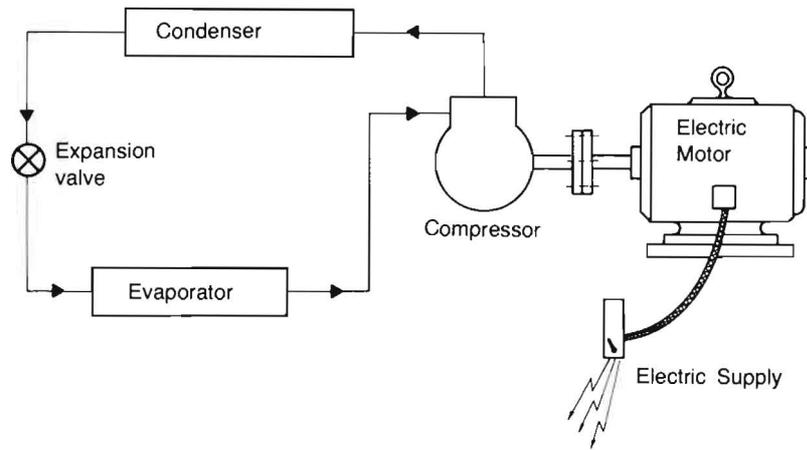


Fig. 2. Electric motor driven vapor compressing cooling system.

2.3 Internal Combustion Engine Driven Vapor Compression Cooling System (ICEDVC):

The ICEDVC configuration shown in Figure 3 uses an internal combustion engine to drive the compressor. Here, the system is also of the open type. However; no solution for the seal is available.

The ICEDVC does need a cooling tower or an air cooled radiator for the engine itself.

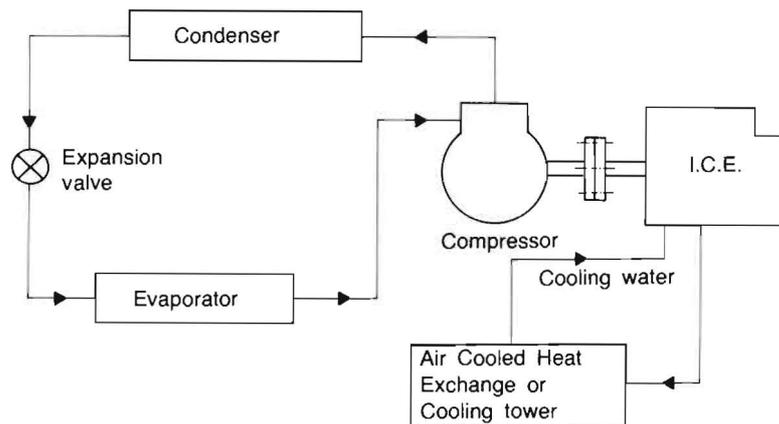


Fig. 3. Internal combustion engine driven vapor compression cooling system.

2.4 Ammonia Water Absorption Cooling System (NH_3A)

The absorption system has proven to be one of the most suitable methods for refrigeration and air conditioning in industry. Basically, an absorption system is not very different in operation from the familiar compression system. A typical system consists of a condenser, a throttling device, and an evaporator. Instead of using a compressor in the vapor compression system, an absorber and a generator are used to produce the so-called thermo-compression. The thermo-compression system is based upon the chemical affinity of the absorbent and the refrigerant. This system needs thermal energy as opposite to the mechanical energy required for the vapor compression system. Thermal energy may be supplied from any heat source. Solar and waste heat can be used, since the temperature levels are low enough to be generated by such sources. Figure 4 shows a schematic of an ammonia (NH_3) water absorption cooling system (NH_3A).

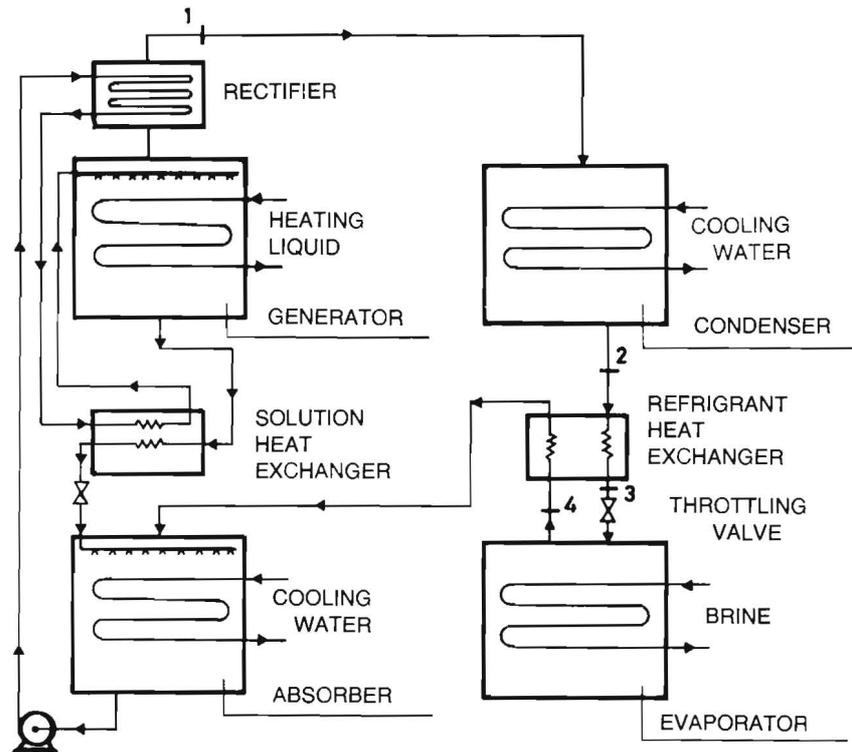


Fig. 4. Ammonia (NH_3) water absorption cooling system.

2.5 Lithium Bromide Water Simple Absorption Cooling System (Li Br SA)

In an Li Br SA system, water is the refrigerant and the Li Br salt is the absorbent. This system is similar to the NH_3 A of Figure 4. However; because of the very high evaporation temperature of Li Br, a rectifier is not any more needed. Also, one heat exchanger is omitted from the system. However, the system requires a wet cooling tower, which consumes a huge amount of water. Cooling towers also require continuous maintenance by qualified technicians, who are not always available.

2.6 Lithium Bromide Water Dual Absorption Cooling System (Li Br DA)

The Li Br water dual cycle shown in Figures 5 and 6 is one of the solutions recommended to overcome problems associated with cooling towers water consumption. The dual cycle may be described by two sequential simple absorption cycles: high temperature level cycle (HTLC) and the low temperature level cycle (LTLC). The HTLC serves the LTLC in supplying its required generator heat and; at the same time, cools its absorber and condenser. The dual cycle has the advantage of avoiding the use of a wet cooling tower as well as of being powered by low temperature heat sources.

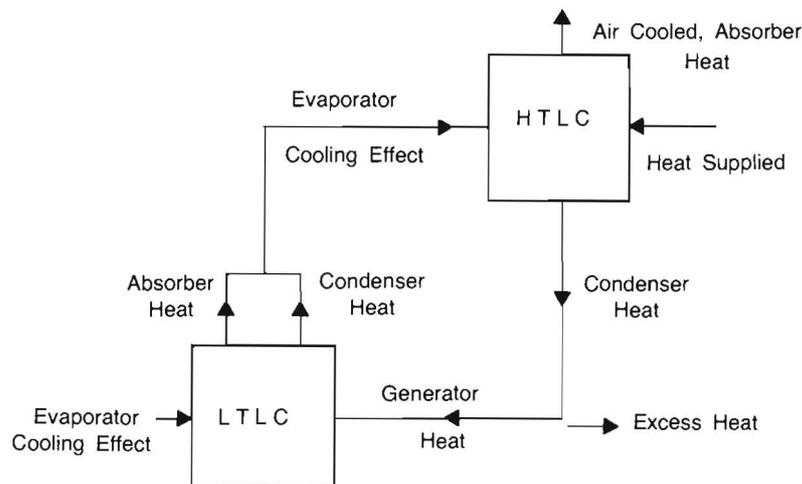


Fig. 5. Li Br-water dual cycle.

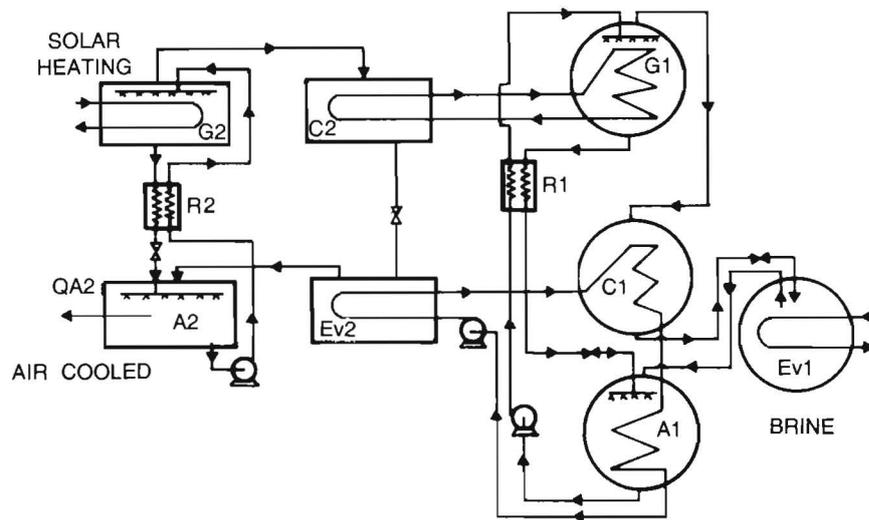


Fig. 6. Air cooled low grade heat lithium bromide-water dual absorption cooling system.

3. Criteria and Subcriteria for Air Conditioning Systems in Saudi Arabia

Table 1 lists the proposed criteria and subcriteria which are recommended for air conditioning systems in the Kingdom of Saudi Arabia. Those criteria are: cooling water, capital cost, running cost, maintenance, spare parts, design and installation, and technological availability and experience.

3.1. Cooling Water

The cooling water may be considered as one of the most important criteria affecting the air conditioning and refrigeration system in arid zones in general, and in Saudi Arabia in particular. Many people in Saudi Arabia, after so many years of experience with cooling towers and systems, believe that using water in air conditioning systems should be avoided as much as possible. This because of many reasons like the scarcity of water in the Kingdom, water salinity, and its corrosion effect. The rating of EMDVC, NH_3A , and Li Br DA systems is very good as indicated in Table 1. This is because the cooling towers are not needed for these systems, while there is a need for cooling towers in the case of a Li Br SA system.

3.2. Capital Cost

To compare the capital cost of the five air conditioning systems in Saudi Arabia, the following cost items are considered:

- (a) Cost of power which supplies the compressor work or the generator heat to the vapor compression and absorption systems respectively.
- (b) Cost of cooling systems, cooling water and cooling towers cost, and
- (c) Cost of required connections and pumps between the system elements.

3.3 Running Cost

Cooling water consumption represents a major running cost factor. This may not be the case in most parts of the world; however, in the Kingdom of Saudi Arabia, the running cost of the cooling water may exceed that of the fuel.

3.4 Maintenance, Spare Parts, Design, Installation, Technological Availability and Experience

In developing countries, these items are of vital importance and could be in some situations the only selection criteria irrespective of the rank of other criteria. Consequently, it is highly recommended to consider these factors precisely and for each sector in the Kingdom as well. Indeed, in highly populated sectors like Riyadh, Jeddah, or Dhahran, these criteria are not as complicated as in the case of low-populated sectors.

4. Analysis

Since there are seven main criteria influencing the selection of air conditioning systems in Saudi Arabia, it is necessary to use one of the multi-attribute decision methods. Fuzzy sets theory is found to be most suitable for finding an optimal system for air conditioning in the Kingdom of Saudi Arabia. Decision analysis using fuzzy sets has three main steps:

1. Criteria weights
2. Rating
3. Ranking and preferability.

4.1 Criteria Weights

Since some of the criteria are more important than others, different weights should be assigned to different criteria to illustrate the difference in the importance of each criterion. To indicate the relative importance of differences between criteria, verbal weights are used.

These weights may be represented by the membership function shown in Figure 7, or by the fuzzy set, W_j (Bass and Kwakernaak 1977):

$$\begin{aligned}
 W_j &= [w_j, W_j(w_j)], j = 1, 2, \dots, n \\
 W_j &= \text{very important} &= [(0.8, 0.0), (0.875, 0.5), (0.95, 1.0), \\
 & & (0.975, 0.5), (1.0, 0.0)]
 \end{aligned}$$

$$\begin{aligned}
 W_j = \text{important} &= [(0.6,0.0), (0.7,0.0), (0.8,1.0), \\
 &\quad (0.9,0.5), (1.0,0.0)] \\
 W_j = \text{moderately important} &= [(0.3,0.0), (0.4,0.5), (0.5,1.0), \\
 &\quad (0.6,0.5), (0.7,0.0)] \\
 W_j = \text{rather unimportant} &= [(0.0,0.0), (0.1,0.5), (0.2,1), \\
 &\quad (0.3,0.5), (0.4,0.0)] \\
 W_j = \text{very unimportant} &= [(0.0,0.0), (0.025,0.5), (0.05,1.0), \\
 &\quad (0.125,0.5), (0.2,0.0)].
 \end{aligned}$$

The weights for different criteria and subcriteria are shown in Table 1.

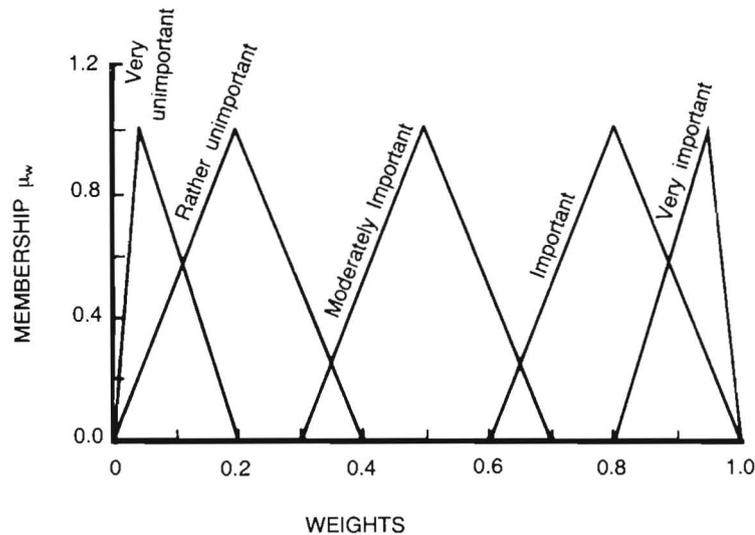


Fig. 7. Membership functions for different weights.

4.2 Rating

Each alternative is rated verbally with respect to each criterion alone, independent of all other alternatives. The rating may be represented by the membership function shown in Figure 8 or by the fuzzy rating of an alternative R_{ij} , where R_{ij} is given by:

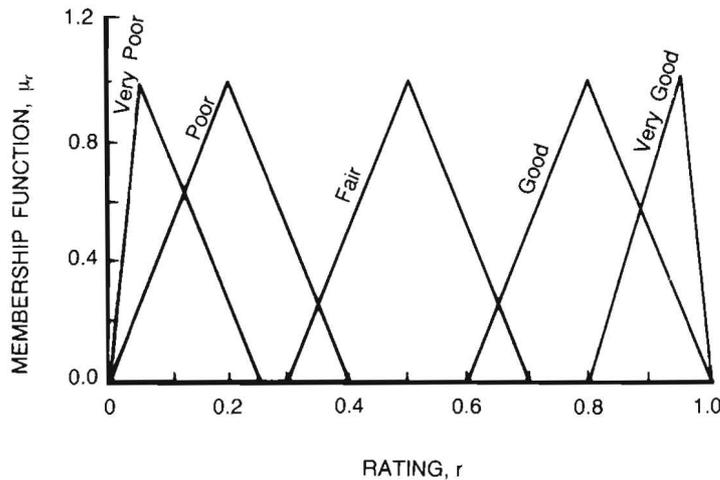


Fig. 8. Membership functions for different ratings.

$$R_{ij} = [r_{ij}, R_{ij}(r_{ij})], \quad i = 1, 2, \dots, m$$

$$j = 1, 2, \dots, n$$

$$R_{ij} = \text{very good} = [(0.8, 0.0), (0.87, 0.5), (0.95, 1.0), (0.975, 0.5), (1.0, 0.0)]$$

$$R_{ij} = \text{good} = [(0.6, 0.0), (0.7, 0.5), (0.8, 1.0), (0.9, 0.5), (1.0, 0.0)]$$

$$R_{ij} = \text{fair} = [(0.3, 0.0), (0.4, 0.5), (0.6, 0.5), (0.5, 1.0), (0.7, 0.0)]$$

$$R_{ij} = \text{poor} = [(0.0, 0.0), (0.1, 0.5), (0.2, 1.0), (0.3, 0.5), (0.4, 0.0)]$$

$$R_{ij} = \text{very poor} = [(0.0, 0.0), (0.025, 0.5), (0.05, 1.0), (0.15, 0.5), (0.25, 0.0)]$$

The ratings for the criteria and subcriteria above are also shown in Table 1.

4.3 Ranking and Preferability

To find out the ranking of each alternative as well as the preferability of the best alternative. IFDA computer program (Sofrata and Abdul Fattah 1982) is used in this analysis. The results are listed in Table 2, through Table 5, and are shown in Figure 9 and Figure 10. Table 2, Table 3, and Table 4 list the final membership, final rating, ranking of each criteria for the five alternatives of air conditioning systems in Saudi Arabia, respectively. Table 5 lists the final membership, rating, and ranking of each alternative. Finally, Figure 9 illustrates the final ranking membership function for the five alternatives of air conditioning, while Figure 10 shows the degree of preferability of the Li Br DA compression system over the other alternatives.

Table 1. List of criteria and subcriteria recommended for air conditioning systems in Saudi Arabia with weights and ratings for each system.

Criteria	Weight	Sub-Criteria	Weight	Alternatives				
				EMDVC	ICDVC	NH ₃ A	Li Br SA	Li Br DA
1. Cooling Water	VI	1.1 Availability	VI	VP	VP	VG	VP	VG
		1.2 Distance	RUI	VG	P	VG	VP	VG
		1.3 Cost	I	P	P	VG	VP	VG
2. Capital Cost	MI	2.1 Power Plant	VI	P	G	P	VG	VG
		2.2 Cooling Systems	VI	VP	VP	P	VP	G
		2.3 Cooling Tower	I	VP	VP	VG	VP	VG
		2.4 Connections	MI	VG	P	G	G	P
3. Running Cost	MI	3.1 Power	VI	G	G	G	VG	VG
		3.2 Cooling Systems	VI	P	P	G	P	VG
		3.3 Cooling Tower	I	VP	VP	G	VP	VG
4. Maintenance	VI	4.1 Conventional	I	VG	P	G	G	G
		4.2 Very skill	VI	VG	VP	P	G	G
		4.3 Cost	MI	VG	VP	P	F	F
5. Spare Parts	VI	5.1 Conventional	I	VG	P	G	G	G
		4.2 Very skill	VI	VG	VP	P	G	G
		4.3 Cost	MI	VG	VP	P	F	F
6. Design & Installation	VI	6.1 Design simplicity	RUI	VG	F	G	G	F
		6.2 Installation simplicity	I	VG	F	G	G	G
		6.3 Safety	VI	P	G	R	VG	VG
7. Technological availability & experience	I	7.1 Conventional	I	G	G	G	G	G
		7.2 Non Conventional	VI	G	G	G	G	VP

Table 2. The final membership function of each Criterion on for the Five alternatives of air conditioning systems in Saudi Arabia.

Criteria	Alternative				
	EMDVC	ICEDVC	NH ₃ A	Li Br SA	Li Br DA
Cooling water	.00000E+00	.00000E+00	.10000E+01	.00000E+00	.10000E+01
Capital cost	.00000E+00	.00000E+00	.12058E+00	.19261E+00	.10000E+01
Running cost	.00000E+00	.00000E+00	.57146E+00	.00000E+00	.10000E+01
Maintenance	.10000E+01	.00000E+00	.00000E+00	.47239E+00	.47239E+00
Spare Parts	.19171E+00	.10000E+00	.28110E+00	.28110E+00	.28110E+00
Design & Installation	.28535E+00	.58460E+00	.77062E+01	.10000E+01	.95002E+00
Technological availability & experience	.10000E+01	.10000E+01	.10000E+01	.10000E+01	.97551E+01

Table 3. The final rating of each criteria for the five alternatives of air conditioning systems in Saudi Arabia.

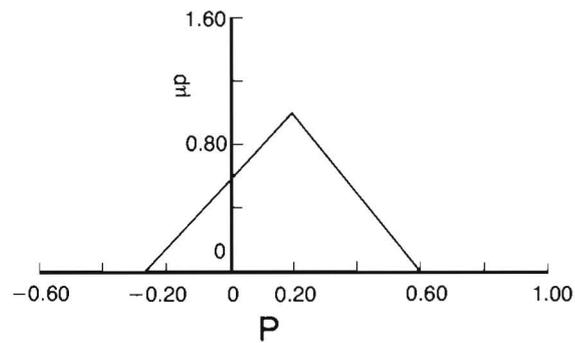
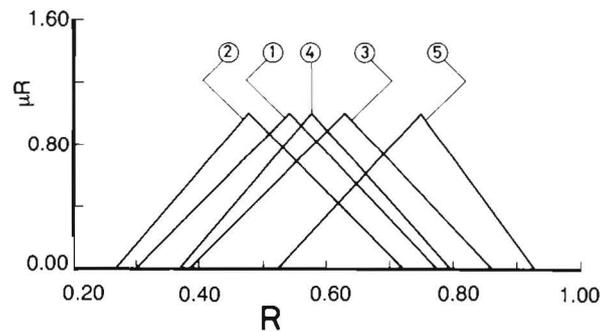
Criteria	Alternative				
	EMDVC	ICEDVC	NH ₃ A	Li Br SA	Li Br DA
Cooling water	.30632E+00	.27213E+00	.95238E+00	.17387E+00	.95238E+00
Capital cost	.27213E+00	.44177E+00	.52200E+00	.55424E+00	.85925E+00
Running cost	.47515E+00	.47515E+00	.83333E+00	.49823E+00	.95238E+00
Maintenance	.95238E+00	.24660E+00	.53804E+00	.79946E+00	.79946E+00
Spare Parts	.61876E+00	.89587E+00	.06658E+00	.66583E+00	.6658E+00
Design & Installation	.65774E+00	.75081E+00	.55623E+00	.89002E+00	.87312E+00
Technological availability & experience	.83333E+00	.83333E+00	.83333E+00	.83333E+00	.51440E+00

Table 5. The final membership, rating, and ranking of the five alternatives of the air conditioning systems in Saudi Arabia.

Alternatives	Final Membership	Final Rating	Final Ranking
EMDVC	.55126E+00	.66877E+00	4
ICEDVC	.42622E+00	.61721E+00	5
NH ₃ A	.73958E+00	.74305E+00	2
Li Br SA	.61611E+00	.69499E+00	3
Li Br DA	.10000E+01	.84103E	1

Table 4. The final ranking of each criterion for the five alternatives of air conditioning systems in Saudi Arabia.

Criteria	Alternative				
	EMDVC	ICEDVC	NH ₃ A	Li Br SA	Li Br DA
Cooling water	2	3	1	4	1
Capital cost	5	4	3	2	1
Running cost	4	4	2	3	1
Maintenance	1	4	3	2	2
Spare Parts	3	1	2	2	2
Design & Installation	4	3	5	1	2
Technological availability & experience	1	1	1	1	2

**Fig. 9.** Preferability of Li Br-water dual absorption system over the other alternatives.**Fig. 10.** Relative rating of cooling systems alternatives.

5. Conclusion

The results given in Table 5 show that the Li Br DA is the best air conditioning cooling system to be used in the Kingdom of Saudi Arabia and the NH_3A absorption system is the second best. In the market, the electric motor driven vapor compressor cooling system (EMDVC) is the most popular system; nowadays, in the Kingdom of Saudi Arabia. However; in the future, the Li Br absorption dual system is expected to become more attractive than the EMDVC system for of two reasons: First, the Li Br absorption dual system requires; at this time, special skill for maintenance spare parts care, complex design and installation care which is not the case for the EMDVC system. But, this situation is expected to change in the future. The second reason is that air conditioning cooling systems may be needed for use in some areas where there is no abundant electric power. In this case, the Li Br absorption dual system will be the best.

References

- Baas, S.M. and Kwakernaak, H. (1977) Rating and ranking of multiple-aspect alternatives using fuzzy sets, *Automatica*, **13**: 47-58.
- Bellman, R. and Giertz, M. (1973) On the analytic formalism of the theory of fuzzy sets, *Inform. Sci.*, **5**: 149-156.
- Capocelli, R.M. and De Luca, A. (1973) Fuzzy sets and decision theory, *Inform. Control*, 446-473.
- Chang, S.L. (1972) Fuzzy mathematics, Man and his environment, *IEEE Trans. Syst., Man., Cybernetics*, **SMC-2**, 92/93.
- Graines, B.R. (1976) Multivalued logics and fuzzy reasoning. *Workshop on discrete systems and fuzzy reasoning*, Dept. of Elect. Eng., Univ. of Essex, Colchester, Essex, England.
- Graines, B.R. (1976) Foundations of fuzzy reasoning, *International Journal Man-Machine Studies*, **8**: 623-632.
- Kenarangui, R., Husseiny, A. and Sabri, Z. (1980) A comprehensive formal approach to the evaluation of bids for desalination plants using verbal judgement, *Desalination Journal*. **9**: 331-336.
- Sofrata, H., Abdul-Fattah, A.F. (1982) Solar powered dual absorption system selection criteria using fuzzy-decision analysis, *Proceedings of the International Symposia on Alternative Energy Sources and Technology*, San Francisco, U.S.A.
- Sofrata, H., Abdul Fath, A.F. (1985) An Interactive Multi-Attribute Fuzzy Decision Analysis Package, *Arab Gulf J. scient. Res.* **3**: 807-815.
- Sofrata, H., Khoshaim, B., Nasser, A. (1979) A solar powered Li Br absorption system, *2nd Miami International Conference on Alternatives Energy*, Miami Beach, Florida, U.S.A.
- Sofrata, H., Khoshaim, B., Nasser, A. and Megahed, M. (1981) A solar powered Li Br dual cycle, *Applied Energy*, **9**: 185-189.
- Sofrata, H., Nasser, A. and Megahed, M. (1981) The coefficient of performance of a solar absorption dual cycle, *Applied Energy*, **8**: 275-284.
- Sofrata, H., Nasser, A., Shibl, A. and Megahed, M. (1980) A study of the solar Li Br dual cycle characteristics, *AIAA 18th Aerospace Sciences Meeting*, Pasadena, U.S.A.
- Watson, S.R., Weiss, J.J. and Donnell, M.L. (1979) Fuzzy decision analysis, *IEEE Transaction on Systems, Man., and Cybernetics*, **SMC-9**, No. 1.
- Whitlow, E.P. (1966) Trends of efficiencies in absorption refrigeration machines, *ASHRAE Journal*, **44**: 256-259.

- Zadeh, L.A.** (1965) Fuzzy sets. *Inform. Control*, Vol. **8**: 338-342.
- Zadeh, L.A.** (1972) A fuzzy set theoretic interpretation of linguistic hedges, *Journal of cybernetics*, **2**: 610-612.
- Zadeh, L.A.** (1976) A fuzzy algorithmic approach to the definition of complex or imprecise concepts, *International Journal Man-Machine Studies*, **8**: 249-258.

(Received 19/12/1984;
in revised form 02/03/1985)

ترشيح نظام تكييف مناسب للمناطق الجافة باستخدام النظرية ذات العوامل المبهمة

عبد الرحمن فؤاد عبد الفتاح و حامد صفراطة

قسم الهندسة الكهربائية، وقسم الهندسة الميكانيكية - كلية الهندسة -
جامعة الملك سعود - الرياض - المملكة العربية السعودية

إن معامل الأداء بشكله المتعارف عليه قد يسبب أخطاء كبيرة
لصاحب قرار الاختيار لنظام تبريد معين، ذلك لأن هذا
التعريف لمعامل الأداء يهمل في مضمونه عوامل أخرى كثيرة
قد تكون أحياناً هي المؤثرة على الأداء.

بناء على هذا فقد وجد أن الطريقة المثلى لاتخاذ القرار
المناسب هي استخدام النظرية ذات العوامل المبهمة لتحديد
أنسب طرق التكييف الواجب استخدامها في الأماكن الجافة
والصحراوية.

وقد تم اختيار المملكة العربية السعودية كمثال
للدراسة حيث تم تحديد سبع عوامل رئيسية تحتوي على
عشرين عامل جانبي.

وقد تم استخدام برنامج حواري مبني على نظرية
العوامل المبهمة حيث يمتاز هذا البرنامج باستخدامه مقاييس
وصفية وليست عددية عند تحديد قيم المعايير المختلفة.

وقد توصل البحث إلى أن نظام الامتصاص المزدوج هو
الحل الأمثل يليه نظام الامتصاص بالنشادر.