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Survey and Review of Refrigerant Leakage Sources and Solutions in Malaysian Refrigeration and Air Conditioning (RAC) Systems

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Abstract: Leakage of refrigerants is one of the most common faults in refrigeration, air conditioning, and Heat Pump (RACHP) systems. Knowledge of leakage sources is critical for minimizing the leakage of high global warming potential refrigerants and the safe application of flammable refrigerants. Data on leak sources causes, and remedies in the Malaysian cooling and refrigeration industry are lacking. This study aims to investigate the potential leak areas that appear during service and maintenance in Malaysia. A structured questionnaire survey was conducted with the participation of 35 stakeholders in the RACHP. The study found that flare fittings and brazing joints are the most observed leak sources in RACHP systems in Malaysia, causing significant refrigerant emissions and energy losses. A desktop study was conducted to identify leakage prevention solutions. This study categorized the solutions into three main pathways: adherence to best practices, strengthening standards of leak testing and prevention protocols, and utilization of alternative joining methods. The application of these prevention solutions will minimize the direct and indirect impacts of refrigerant leakage.

Keywords: refrigeration system; leakage; flared joints; brazed joints; energy efficiency

1. Introduction

The refrigeration, air conditioning, and heat pump (RACHP) industries are significant contributors to the dilemma of ozone depletion and global warming, associated with the direct and indirect impacts of refrigerants[1)]. The direct impact of RACHP systems is mainly due to the leakage of refrigerant gases during the operation of the RACHP unit, improper handling of refrigerant during installation, and improper disposal of the unit during its end-of-life. The indirect effect results from the energy use of the system and fossil fuel consumption to produce the electricity required to run the system[2)]. In addition to climate impacts and ozone depleting effects, there are other concerns regarding the leakage of refrigerants in RACHP systems[3)]. Leakage is a multi-billion-dollar problem for the global air conditioning and refrigeration industry, and represents a high cost in terms of energy use and maintenance costs [4)]. Leakage decreases the efficiency of the RACHP system owing to the loss of refrigerant charge, leading to subsequent problems such as improper functioning of the equipment to maintain space comfort, increased operation and maintenance costs, and eventual failure of premature system components such as compressor[5)].

In addition, refrigerant leakage is one of the most frequently encountered faults in compressor-based appliances, which are mainly used for refrigeration and air conditioning purposes[6)]. Although refrigerant release into the atmosphere might occur during any stage of its life cycle, it mostly occurs during the service and maintenance of equipment due to leaks in various components of RACHP systems[7)]. Most RACHP appliances reportedly have a 10% annual leakage rate due to limitations in joining techniques, system design, operation, poor maintenance practices, etc. likes[8)]. Safety standards, however, have used a range of assumed and inconsistent leak rates that maybe unreasonable[9)].

Furthermore, the leakage rate among RACHP systems varies depending on several factors, such as the operational environment of the system, number of individual fittings used, number of field-made joints, and other considerations [8)].

The leak rate also varies depending on the refrigerant type used in the RACHP equipment owing to variations in the combination of physical properties, flammability rating, and system design differences between refrigerants. The leakage rates for R134a, R410A, and R32 refrigerants are 12%, 15%, and 20% respectively. The amount of leaked refrigerant must be refilled annually to ensure uninterrupted operation of the RACHP system[10)].

Due to the growing demand for cooling and refrigeration and the wide use of hydrofluorocarbons (HFCs), HFC emissions are increasing. According to a study by Gschrey et al. [11)], contribution of F-gases to global warming will increase from 1.3% (2004) to 7.9% (2050) of total CO2 emissions in the business-as-usual scenario. HFC emissions are mainly associated with a lack of proper refrigerant management practices[12)]. Given the growing global demand for cooling due to global warming and the increasing share of cooling in GHG emissions, refrigerant management covering leakage prevention is considered one of the most impactful actions for climate change mitigation in the future[13)]. It is crucial to emphasize refrigerant management, which involves identifying leak sources, leak testing, detection, prevention, and the effective recovery and demolition of refrigerants. Therefore, gathering information regarding the sources of refrigerant leakage is of paramount importance for identifying and prioritizing leak prevention measures in RACHP systems[14)].

Throughout the literature, there are several studies related to leakage and its sources in RACHP systems as reported, e.g., by Francis et al.[15)], Jain et al. [16)], Koranaki et al. [2)], Colbourne et al.[9)], ETSU[17)], Cowan et al.[27)], and Brodribb and McCann[18)]. Francis et al.[15)] investigated refrigerant leakage sources in the UK's commercial refrigeration sector, including standalone, condensing unit, and full supermarket systems, which mainly use R404A and R134a refrigerants. According to Francis et al.[15)], leakage mainly occurs at brazed joints, cracked surfaces, compressor packs, and high-pressure liquid lines. Furthermore, more than 82% of leaks in refrigeration systems originate mainly from joint failures of pipes or a leaking seal in the compressor pack and high-pressure liquid line. Jain et al.[16)] studied leakage detection using a smart thermostat on refrigeration units of 74 retail enterprises in a city in India and reported that leakage occurs at the coils or valves of the refrigeration unit, slowly diminishing the cooling capacity of the unit while allowing it to be functional.

Tassou and Grace [5)] investigated refrigerant leakage detection using a real-time monitoring approach in a liquid-to-liquid chiller experimental system using R404a as refrigerant. According to Tassou and Grace [5)], industrial and commercial refrigeration systems leak the refrigerant gradually at the joints or seals, which usually remain undetected for long periods of time until sufficient refrigerant is lost, adversely affecting the operation of the RACHP system. Furthermore, the leak can originate from mechanical failure or accidental rupture of a pipe or joint owing to catastrophic damage. An accidently vented refrigerant during service may also result in leakage[5)].

Koronaki et al.[2)] studied refrigerant leakage and prevention in domestic and commercial RACHP systems across Europe and mentioned that the leakage possibly occurs at joints, seals, gaskets and cracked pipes, as well as from safety relief devices. ETSU[17)] studied the leakage sources in a refrigeration system and found that there are six common leakage areas namely: flare joints, shaft seals, other mechanical joints, signal lines/small bore lines, valves/glands, and vibration (chaffing) in refrigeration systems. Colbourne et al. [9)] investigated positions of leak holes and sizes in RACHP systems containing flammable refrigerant (e.g., R290) and found that leak hole positions include Schrader valves, capillary tubes, various types of valves, within tubing, at connections/joints, within condensers and evaporator (primarily at return bends), filter dryer and vibration dampers. These leaks represent 2%–20% depending on the type of system.

Although, the refrigerant leakage sources and causes in commercial RACHP systems have been investigated by comprehensive international studies including the USA Environment Protection Agency Greenhill program[19)], a UK study of two supermarket chains[15)], European Real Zero work[20-21)] , and Refrigerant emissions in Australia, Sources, causes and remedies[18)]. To the authors' knowledge, studies on leakage sources and solutions are lacking in the literature in the context of the Malaysian RACHP industry. Only a limited number of studies, including that by Nazif et el. [22)], Taib et al. [23)], and the APEC Energy Working Group [24)] investigated the leakage issue as part of fluorocarbon management in Malaysia and the ASEAN region, focusing mainly on residential, commercial, and industrial air-conditioning and refrigeration systems. Given the growing contribution of refrigerant emissions to global warming, the number of studies regarding sources of leakage and solutions is insufficient and needs to be studied exentsively.

This study addressed two main questions regarding refrigerant leakage. First, what are the sources of leakage in RACHP systems in Malaysia? Second, what are the long-term technical solutions for preventing leakage in residential, commercial, and industrial refrigeration and air conditioning systems? This study aims to provide a clear insight into the aforementioned questions considering Malaysian RACHP industry conditions and constraints. To do so, the study used a combined method of structured questionnaire survey and desktop study to obtain the objectives. The study results will be helpful for the development of refrigerant management as well as the improvement of energy efficiency in RACHP systems. The findings are also of increasing importance for the safe application of flammable refrigerants, especially hydrocarbons such as R290, as alternatives to HFC refrigerants.

2. Literature Review

2.1 Status of RACHP Sector in Malaysia

Malaysia is referred to A5 parties-Group 1 under the Kigali Amendment of the Montreal Protocol. According to the requirement of the Government of Malaysia (Department of Environment) and the Montreal Protocol to manage fluorocarbon gases, the use of CFC refrigerants was banned entirely in Malaysia, and the consumption of HCFCs (e.g., mainly R22) is expected to be completely phased out by 2030. In addition, the consumption of HFCs is in the process of phasing down and being replaced by low GWP refrigerants. Currently, the commonly used refrigerants in the Malaysia's cooling and refrigeration industry are R22 (e.g., in old equipments) and 410A, R134a, and R404A, which are high global warming potential refrigerants. In addition, a few natural low GWP refrigerants such as Hydrofluoroolefins (e.g., R-1234yf), Hydrocarbons (e.g., R-290, R-600a), and Ammonia are used, but they are limited [23].

To date, the control of refrigerant in Malaysia has focused only on import/ export activities and the production of refrigeration and air-conditioning units. There is no enforced regulation focusing on the technical control measures available in the country to prevent the release of fluorocarbon gases into the environment[22]. There is no mandated regulation on the proper management of refrigerants. The country also faces a lack of proper collection and disposal facilities and suffers a very low level of awareness among the relevant sectors and equipment users regarding the importance of proper treatment of refrigerant and the negative impacts of refrigerant emissions[23]. Therefore, in the context of refrigerant management programs to reduce its environmental and energy use impacts, good monitoring, maintenance, and servicing including leakage prevention, are of particular importance.

2.2 Refrigerant leakage condition and impacts

Leakage is any undesirable opening, hole or porosity in a closed medium containing refrigerant fluid and allows the refrigerant to escape into the air due to the pressure difference between the containment and the outside. It occurs in all types of RACHP systems.

The majority of refrigerant leakage is from gradual minor leaks during operation that are left undetected for long periods of time[18]. The leak mass flow rate is a function of the thermodynamic properties of the leaking fluid and varies widely among the refrigerants. As such, the assumed leak mass flow rate is determined for the specific refrigerant being applied in a RACHP system [9]. According to a comprehensive survey of systems across a wide range of HFC refrigerant charges by Japan's Refrigerants and Environment Conservation Organization (JRECO), the average leak mass flow rate is 0.16 g min^{-1} based on vapor leaks, with a hole size between 0.002 to 0.005 mm^2. The largest mass flowrate is almost 3.0 g min^{-1}, giving a hole size of 0.04 to 0.07 mm^2. In multi-split AC systems, the biggest leak is 6.0 g min^{-1} of R32 vapor at 10°C and 67 g min^{-1} of liquid at 63°C, with a theoretical leak hole of 0.045 mm^2 in the indoor units. In the outdoor units of multi-split AC systems, the largest flowrate is 58 g $min^{-1}$of R32 vapor and 660 g min^{-1} of liquid, resulting in a theoretical leak hole size of 0.45 mm^2.

Commercial refrigeration systems comprise many components joined together in sub-assemblies (e.g., individual tubes in a heat exchanger). They are attached to other major components such as compressors, and connected to a piping system to distribute the thermal energy. Further, the system components are connected by joining technologies, which create a mechanical bond between them. Joining components helps in supporting their weight and operational stress of the system and allows the working fluid to continue its path throughout the system. There are several joining methods in RACHP industry namely brazing, flaring, compression fitting, crimp fitting, hybrid joining, and so forth[25].

Brazing is the most common joining method in RACHP systems to ensure a leak-tight seal. It is the method of joining by means of heat via a suitable flame and the application of a filler material. However, it has some drawbacks such as the risk of using an open flame, the difficulty of joining two dissimilar metals, and so on. [4]. Flaring joint is an alternative joining method, which is used when the use of an open flame is either not desirable or impractical[26]. Flare joint creates a leak free seal, however, in the long-term, it experiences fatigue over time.

Another method of joining is press-connect fitting. It is an elastic O-ring fitting to create a leak free seal that is usually applied in potable water supply applications and has also been proved to be a reliable joining technique in plumbing and HVAC applications. The O-ring fitting is chemically compatible and structurally sound to work with the common refrigerants in use today such as R134a, R410A, and R404A. It is elastic enough to make a leak-tight seal when compressed[4]. Table 1 shows the characteristics and operating conditions for the aforementioned fitting types.

Table 1 Application parameters for each fitting type specified by piping manufacturers [27].

Fitting type	Brazed	Press	Compression	Flare (45°)
Maximum working pressure	28 bar (400 psi)	48 bar (700 psi)	38 bar (550 psi)	38 bar (550 psi)
Temperature range	0 to 90 °C (32 to 200 °F)	-40 to 149 °C (-4 to 300 °F)	-54 to 93 °C (-65 to 200 °F)	-54 to 121 °C (-65 to 250 °F)
Available tube sizes	3/8 in. to 3-1/8 in. (9.5 to79.4 mm)	1/4 in. to 1-3/8 in. (6.4 to 34.9 mm)	1/8 in. to 1 in. (3.2 to 24.4 mm)	1/8 in. to 3/4 in. (3.2 to 19.1 mm)
Compatible tube materials	Copper	Copper	Copper, aluminum, plastics	Copper, aluminum, brass, steel
Removable?	No	No	Yes	Yes

2.3 Equipment Performance and Energy Consumption

The level of refrigerant charge can significantly affect the optimal performance and efficiency of RACHP systems[21]. In systems having a receiver, however, the performance will not be affected until the liquid level in the receiver has been depleted. Receiver is basically a storage device for containing refrigerant that is not actually in circulation and it can be considered as being an excess refrigerant container. All the flowing refrigerant in a RACHP system passes through the receiver, thus a constant liquid-level is maintained during operation. In non-receiver RACHP systems, overcharging and undercharging the refrigerant will cause higher energy losses, thus lowering the efficiency of system components including the compressor [28].

Poor maintenance service and the refrigerant leakage cause a RACHP system to be undercharged, which in turn results to lower cooling capacity and higher operating costs[21]. If leakage is slow and is left undetected for long periods of time, while allowing the equipment to be functional; it lowers the performance of RACHP equipment and reduce cooling capacity; hence, it takes more time than usual to cool the same space. Consequently, the compressor work is increased resulting to higher energy consumption and increased GHG emissions due to long hours of operation at undercharge condition[14]. According to Goswami et el.[29], 10% reduction in refrigerant level reduces the cooling capacity of the system by 3.5%. When charge losses exceed 20% of the system's initial charge, the system suffers serious degradation of performance. Leakage of 50% is regarded as the breaking point for the performance of the system.

In small RACHP systems such as split air conditioners, leakage of only 5 % of the refrigerant charge can reduce the flow of refrigerant into the evaporator, thus reducing the saturated evaporating temperature. Eventual drop of the evaporative temperature by 1.0 °C, increases the energy consumption by 2-4%. For simple condensing unit evaporator systems such as retail refrigeration and industrial RACHP systems, similar impact on efficiency is witnessed. However, with the liquid receiver the performance will not be affected until the liquid level in the receiver has been depleted [2].

There is no accurate correlation between refrigerant leakage and system's energy performance yet. The impact of leakage on energy consumption varies depending on different systems[2]. According to an experimental study by Japan's Refrigeration and Air conditioning Industry Association (JRAIA)[30], the energy consumption increases considerably along with leakage of the refrigerant. Furthermore, the power consumption rises sharply when the refrigerant contained in the system is diminished to below 62.5% of the full charge. For instance, if the full charge of refrigerant is 8.0 kg, then the reduction of refrigerant level to 5.0 kg from the initial charge of 8.0 kg will increase energy th consumption of equipment at that point. The changes in coefficient of performance (COP) and cooling capacity of refrigerator is shown in Fig. 3.

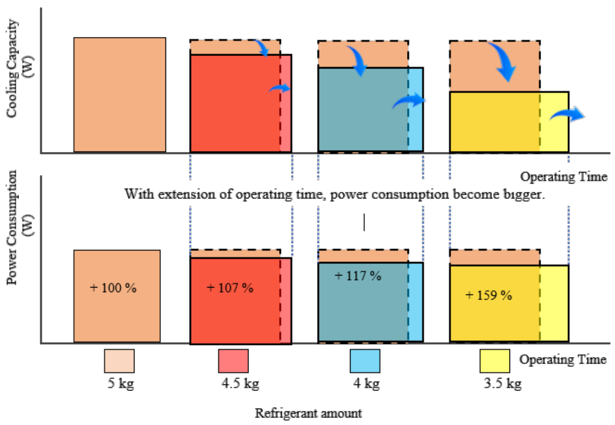

Fig. 1: Impact of decrease in COP on refrigeration capacity and power consumption (JRAIA, 2018).

According to Fig. 1, in a system charged to its maximum cooling capacity or maximum performance (COP), deduction of refrigerant amount from its starting charge will decrease the cooling capacity and increases the power consumption. Drop in the cooling capacity will be recovered by expanding the operating time to produce the required cooling effect. As a result, the equipment operates longer than usual, and hence the compressor does more work resulting to increased energy consumption.

Comparing with no leakage scenario, an increase of 15% in power consumption during 1.75 years after the refrigerant charge level drops to 62.5% of the initial charge[30]. Therefore, detecting the leakage at its early stage is crucial not only from environmental perspective, but is for preventing further power consumption as well. For early detection, continuous monitoring and inspection of the refrigerant level is critically important.

3. Methodology

In this study, a strucrured questionnaire survey was conducted to evaluate the technician's activities during service and maintenance of RACHP equipments. The link of questionnaire was provided in the Google form platform for the target respondentss. The target repsondents for the study were service technicians of companies who are members of the Malaysian Air-Conditioning and Refrigeration Associatetion (MARCA). MARCA is a representative of the RACHP industry in Malaysia who gather all the manufacturing, refrigerant supplier, and service companies under an ambrella in order to promote the industy intesrests, coordinate activities, enhnce standards, foster relationships, and facilitate knowledge sharing among members, while managing funds and expanding its acceptance.

The questionnaire was distributed to 34 stakeholder companies in the RACHP industry and was expected to be filled over two weeks. From the two weeks of survey, we managed to collect feedback from 32 respondents. The technicians in the industry were inquired about the leakage sources, scope of their service, frequency of inspection for leaks, and detection methods. For identifying the leak sources, a list of system-level locations prone to leakage were given in the questionnaires. The participants were asked to nominate the major sources and causes of leaks they had encountered or repaired over the previous 12 to 24 months.

Of the respondents, 72%, 12%, and 16% of the participating RACHP service companies were air-conditioning service companies, refrigeration service, and air-conditioning/refrigeration/refrigerator manufacturers respectively. The target companies had experience ranging from 5 to 15 years in RACHP industry. Most of the respondents have attended service and maintenance related programs including the trainings for refrigerant leakage prevention. Besides, most of the respondent companies had the knowledge of certification of Service Technician Program for RACHP sector issued by Department of Environment (DOE) Malaysia.

For the data analysis, Microsoft Excel software was used to tabulate and analyze the collected data from google form survey. The structured approach used for the analysis included critical information about the leak/fault incident report by technicians (e.g., previous (related) incidents, call out initiator, leak detection method, number of leaks detected, repair actions, and frequency of maintenance) as well as the more basic information about the nature of the faults. In addition to survey, a comprehensive desktop study was conducted to find the technical solutions for prevention of leakage occurring in the mentioned sources.

4. Results and Discussions

4.1 Sources of Leakage

From the total 34 RACHP industry stakeholder companies, 32 of them responded to the questionnaire survey. Analysis of the collected data using Microsoft Excel software indicates that the flare joint/mechanical joint and brazing joints are the most common sources of leakage in RACHP systems, followed by lock ring joint, valves, and flints. Of 32 respondents, 24 technicians which comprise 75% of participants responded that they have frequently encountered leakages at flare joints and mechanical joints indicating high rate of occurrence, while 20 of them (62% of respondents) found leakage at brazing joint and 17 respondents (53%) have witnessed leakage at lock ring/O-ring joint. Only 1 respondent (3% of total respondents) witnessed leak incident occurring in other component such as valves, aluminum coil, and flints. Figure 2 shows the result of survey as described.

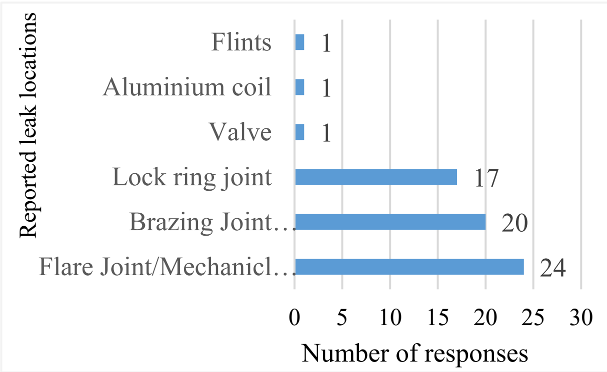

Fig. 2: Leak sources encountered during servicing of RACHP systems.

The extent of validity of responses, however, depends very much on a number of factors that affect the outcome of survey such as the unwillingness of technicians to acknowledge the existence of leaks in their service and how thoroughly the technicians actually looked for leaks. Moreover, the accuracy of results is also affected by other factors such as how busy the technicians were during service and maintenance, and how much time they spent investigating the leak (e.g., the response time) or how late they were. Other determining factors may also include the sensitivity of gas detectors used for leak detection and how lazy the particular technician has been. Given that most of the respondents had received the necessary trainings related to service and maintenance of RACHP systems and possess nessary certifications, the effect of behavioral characteristics of respondents on the validity of survey results can be neglected.

4.2 Scope of Maintenance Service

The respondents were asked about the scope of activities during service and maintenance. Figure 3 highlights the most frequent services covered by the stakeholder companies. The most common services delivered included test run and inspection of equipments (81%), followed by leak test (75%), pressure test (72%), cleaning and finishing (72%), performance tests (69%), equipment repair (66%), charging refrigerant (66%), evacuation and vacuum hold (66%), recovery of HCFC/HFC refrigerants (62%), and seal process (34%). Only one respondent, answered that commissioning, power voltage check, and annual change of oil in compressor were involved in their services.

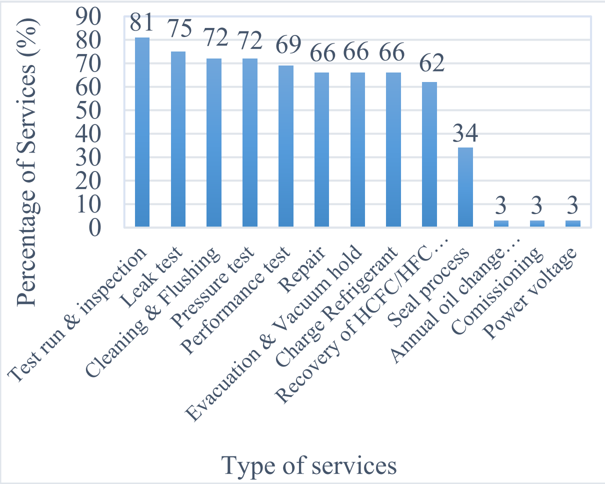

Fig. 3: Scope of services in the RACHP industry

4.3 Frequency of Maintenance Service

Figure 4 shows that the frequency of maintenance and servicing activities are once every 3 months, 6 months, and per year basis depending on different types and sizes of systems, respectively. In air conditioning units, commercial and industrial refrigeration, maintenance activities are conducted every 3 months. In domestic refrigeration systems (refrigerator/ freezer/ refrigerator-freezer), maintenance activities are conducted once every 6 months.

The result shows consistency with the standard period for leak inspection as mentioned in the international guidelines. The actual frequency of inspection in the country might be different with the standard frequency of inspection. In order to accurately assimilate the actual condition of inspection frequency, equipment users also must be included in the survey in future researches.

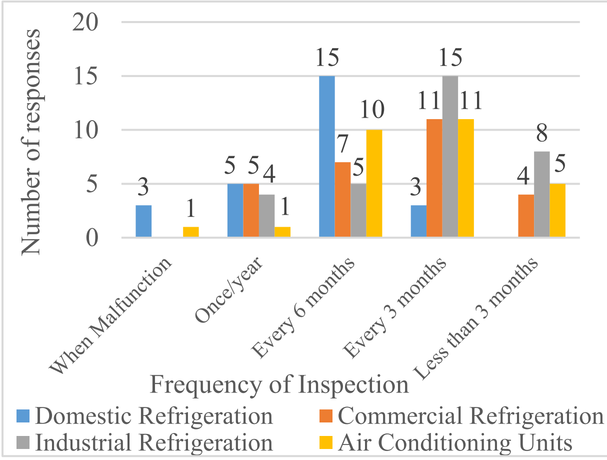

Fig. 4: Frequency of maintenance service and leak inspection by maintenance personnel

4.4 Method of Leak Detection

According to Figure 5, among the three common methods of leak detection namely soap bubbles, hand-held electronic leak detector, and remote monitoring, the RACHP service companies in Malaysia utilize soap bubbles for leak detection, followed by electronic leak detectors, and remote monitoring.

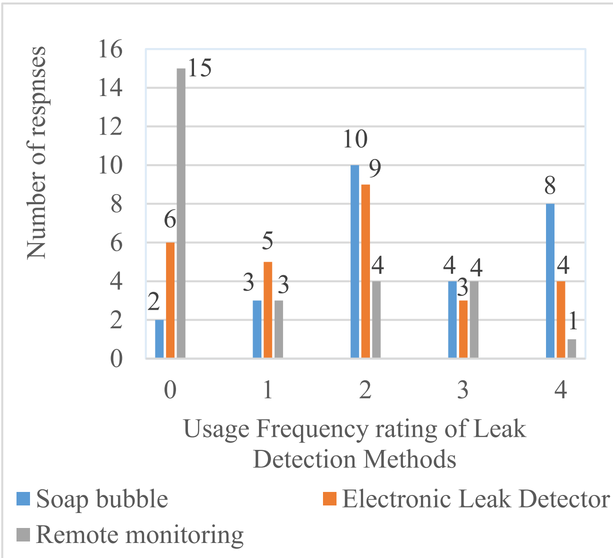

Fig. 5: Common method of leak detection in Malaysia

Table 2 shows the rating numbers used for analysis of the usage frequency of leak detection methods. Based on the rating of the frequency of usage, higher ratings of 4 and 3 belongs to always and often, indicating that the soap bubbles are the common leak detection, followed by electronic leak detection. Furthermore, lower ratings such as 0 and 1 belong to never and rarely, which shows that electronic leak detector and remote monitoring are rarely used when the soap buble solution is not available. In addition, the electronic leak detector is used when the soap bubble solution is not suitable to be used in a specific application.

Table 2. Rating numbers used for detection methods in graph

0	1	2	3	4
Never	Rarely	Sometimes	Often	Always

4.5 Comparison of Findings with Other Studies

The results obtained about the leakage sources in the current study are reflected in the international studies on the causes and sources of refrigerant leakage in the commercial refrigeration, including findings from the USA Environment Protection Agency Greenhill program[19], a UK study of two supermarket chains[15], the European Real Zero project [20-21), 31] and in the Refrigerant emissions in Australia, sources, causes and remedies[18].

Figure 6 indicates that findings of this study is particularly similar to the result obtained by Brodribb and McCann[18] in Australia in which flared fitting and mechanical joint, and brazed joints were the most frequently observed leakage sources.

The comparison included only the major leaks found in both studies, not all of the identified leaks. For the purpose of comparative analysis, the result of leak sources in the current study was converted into percentages of leak occurrence and compared with that of Brodribb and McCann[18]. From the perspective of differences between the two studies and level of details in the findings, the current study included 14 system-level leak location in the survey, while the study by Brodribb and McCann[18] included 18 leak areas in the survey indicating more specificity and comprehensiveness about the leak sources. Another limitation is that the sample size (respondents) in this study was 34 RACHP stakeholder companies. Whereas, in the study by Brodribb and McCann[18], the samples in the survey included over 150 refrigeration system technicians and contracting businesses that were involved in the installation, maintenance, and repair. As shown in figure 8, flare joints are the most common leak location by 88% and 73% in Australia and Malaysia respectively, followed by mechanical joint, brazing joints, and lock-ring/O-ring joint in the next stands.

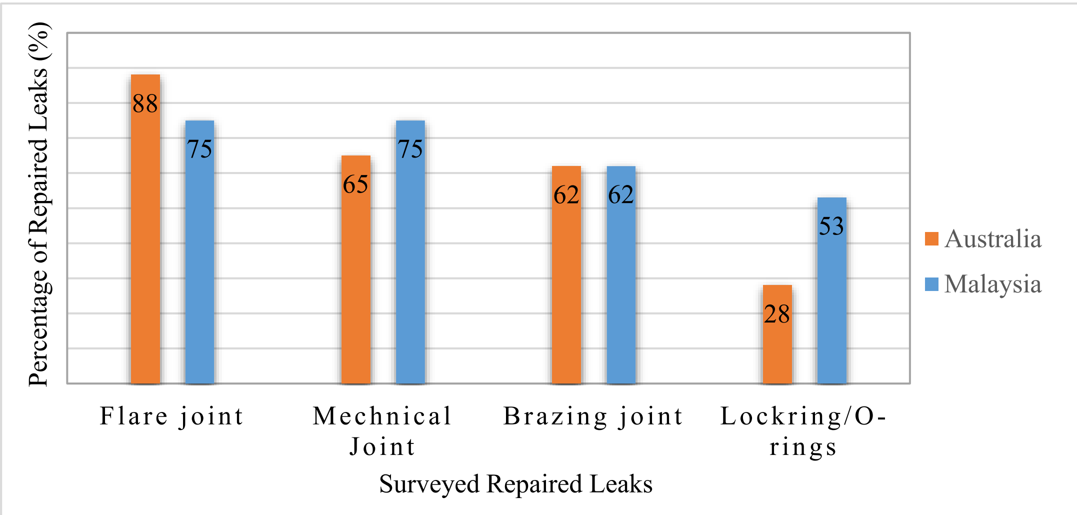

Fig. 6: Comparison of refrigerant leak sources with the Australian RACHP sector.

4.6 Technical Solutions for Minimizing Leakage

Considering the existing literature, a detailed desktop study was conducted in order to identify the gaps and accordingly to propose the technical solution for leakage prevention during service and maintenance in RACHP systems. Based on literature review, the technical solutions for leakage prevention fall under three significantly important pathways: (1) adherence to the best practices by the technician personnel and operator of the RACHP equipment in every single stage of servicing and maintenance involving installation, maintenance, repair, and decommissioning of the system; (2) strengthening existing standards particularly standards relevant to leak testing and leakage prevention; and (3) research, development and utilization of new joining materials and alternative methods in RACHP industry such as hybrid joining connections that combine torque-based fitting with secondary non-mechanical joining technique, fiber laser welding system, and reactive nano-technology multilayer electro joining techniques for leak tight connections in RACHP system. Meeting all these three essential requirements, will ensure a leak tight RACHP system that greatly reduce the total equivalent warming impact (TEWI) of the system as well as save significant amount of energy in the system. The summary of gathered literature on leak prevention measures is in Table 3.

Table 3 Leak prevention measures

Applicability of The Leak Prevntion Measure	Recommendation	Leak reduction measures	References
Flare joint	Strengthening standards	Regulation enforcement, consistent leak standards and testing protocols, revising existing standards, incorporating, and detailing the standing pressure test, bubble test, and vacuum decay test in standards and regulations.	3)
	Adherence to best practice	Avoiding flare joint wherever possible; use factory solder adapters instead of field made flares; follow guidelines of flaring; avoidance of under-tightening and overtightening of flare nuts and avoiding thermal expansion of flare nuts.	2)
Braze joint	Improvement in joining method	Advancement in braze joint sealing technology, and improvements in brazing technique and operation.	32)
	Adherence to best practice	Follow the brazing guidelines (e.g., deburr, clear, and clean the tubing, ensure a good capillary action; use better torch, etc.).	34)
	Adherence to best practice	Follow brazing good practice.	35)
	Adherence to best practice/test method	Good ergonomic practice during brazing process; multiple double testing of U-bended braze joints after brazing.	37)
Flare and braze joints	Adherence to best practice	Upgrading and replacing existing system components with more leak resistant parts, ensure proper valve cap exist on all valve stems, ensure presence of epoxy or phenolic coatings on fine tube surfaces and refrigerant piping.	19)
Press fitting	Alternative joining method	Alternative fittings to brazing connection (e.g., press-connect fitting alternative to brazing in some specific situation to create leak free seal.	4)
Crimp fitting	Alternative method to brazing	Appropriate use of joining method based on operating environment and condition;	33)
Mechanical joints	Adherence to best practice	Critical assessment, training, and competence of technicians, record keeping, in service inspection, leak analysis.	14)
Lock ring and flare joint	test methods/best practice	Conduct fitting durability and leak tests (e.g., pressure cycling test, and burst pressure test, etc.); Use manufacturer tools; apply lock prep anaerobic sealant; correct choice of inserts.	36)
All fitting types	Strengthening test methods/research and development of alternative materials and joining methods	Developing laboratory test methods for effectiveness evaluation of joining methods and component leakage; Develop and use new joining techniques, reduce number of internal joints by new methods and materials; next generation leak detection; self-sealing joints, fittings, and components.	25)
	Adherence to best practice and alternative joining method	Competence based qualification of technicians and training them especially for brazing skills; Use of suitable joining method for different situations.	27)
	Adherence to best practice	Incorporate fixed leak detection sensor in compressor enclosure equipped with alarm system; quick response to leak incident; more frequent leak check for larger systems.	7)

According to the table, employing highly skilled and experienced technicians to install and assemble equipment and components, especially for operations requiring high skills such as brazing, is one of the best practices to prevent leakage[27]. Furthermore, competence-based qualification, further training requirements for technicians to maintain their license, critical assessment, and training of technicians, mainly training them on brazing skills, leak tests, and refrigerant tightening, are other recommendations to tackle the leakage problem the RACHP system[18].

In addition, best practice means record-keeping, in-service inspection, leak analysis[14]; quick response to leak incident, more frequent leak check for larger systems, and incorporating fixed leak detection sensor in compressor enclosure equipped with alarm system fall under best practice pathway and are also significantly crucial for leak reduction[7]. Other general measures in best practice include: avoiding flare joint wherever possible[2] and elimination of flared connections and replacing them with brazed connections; use of flare/ solder adapters inaccessible connections, application and installation of vibration eliminators, and maintaining valves capped in all times with a suitable washer in place[18]. Moreover, the use of Euro flare fitting for quick and easy installation and repair of air-conditioners is advised[36].

When making flare joint, good practice of flaring should be followed, such as proper cutting of the pipe and deburring using correct tool and using the eccentric flaring tool to ensure the correct amount of tube is protruding through flare block. In addition, flare size should not foul the flare nut. Flare nuts need to be lubricated using refrigerant grade oil. During flare making, the operator or technician should use appropriate tools produced by the equipment manufacturer. Under-tightening and overtightening of flare nuts and thermal expansion of flare nuts due to temperature variation should be avoided. Factory solder adapters should be used instead of the field made flares[2]. Similarly, the operator or technician has to follow the same guidelines of good practice in brazing operation. The guidelines covered in the literature involve debut and clearing of the tubing, cleaning the tube, coupling, and filler rod using a 3M scotch-Brite pad, ensuring a tight fit up for good capillary action, purging the tube with Nitrogen, and learning how to use a variety of filler materials. Furthermore, a better torch should be used in brazing, and the operator needs to carry several tip sizes and use carburizing flame for oxyacetylene. When brazing, the tube should be heated, not the filler material or the joint. To apply the filler material evenly, complete the capillary action[34]. In addition, appropriate tools produced by the manufacturer should be used, such as torque wrench, lock-press, cordless assembly tool, assembly jaws, starter kit, and tube deburrer). The choice of inserts should be made correctly and precisely (e.g., brass stabilization insert). Moreover, the lockprep anaerobic sealant should be used to compensate grooves in the tube surface. In brass connecting pieces, Teflon tape is used to protect against corrosion[36].

Furthermore, during field installation of joints, tube lengths need to be measured accurately and then cut properly with a square cut. Any deformities in the structure of the tube should be avoided. The tube then needs to be rammed to remove any burr. The tube surface must be cleaned critically from oxides, soils, oils, and other dirt to ensure the filler material flows evenly into the joint. Avoid the use of corrosive cleaning agents and excessive space around the tube's circumference to prevent crack under vibration situations. Then immediately braze the tube after cleaning, fluxing, and assembling. Overheating the joint must be avoided; clean any flux residue with hot water/wire brush to avoid corrosion in future[35].

In addition, the existing system components should be upgraded and replaced with more leak-resistant parts. For instance, the following measures can be adopted to upgrade the existing system[19].

1. Replacing the discharge-piloted pressure regulating valves with suction stepper valves in evaporator.
2. Replacing the flare connections components with brazing fitting components.
3. Replacing valves having control lines with valves does not require control lines.
4. Replacing valves having bottled connections with hermetic one-piece valves of no mechanical joints.
5. Replacing the fragile cap tube-type control lines with that of steel lines.
6. Mounting of a sealed vertical tee ahead of a solenoid valve to eliminate liquid hammer.
7. Ensuring that equipments located in vulnerable environments has epoxy or phenolic coatings on the fine tube surfaces and refrigerant piping.

Moreover, multiple double testing of U-bended brazed joints after brazing underwater and changing the brazing posture from standing to sitting on a mobile stood during brazing process, can improve brazing performance, cost-saving, and reduce brazing leaks[37]. The other requirements of utmost importance are strengthening the existing standards, guidelines and developing new test methods and evaluation procedures. The existing regulations should be enforced and made stricter, and refrigerant leak standards and testing protocols must be consistent. In addition, the standards need to be clarified and aligned. Moreover, the standing pressure test, bubble test, and vacuum decay test should be incorporated and detailed in standards and regulations[3]. Laboratory test methods should be developed to evaluate the effectiveness of joining methods, evaluating component leakage. Besides, consistent evaluation is necessary to verify both factory-made and field assembled joints[25].

In addition, the codes of practice for the RACHP industry need to be revised. For example, the code of practice on valves to retain leaks and refitting caps with suitable O- rings need to be revised and enforced. Moreover, using shredder valves should be limited by enforcing and defining existing guidelines[18]. Fitting durability and leak tests (e.g., corrosion test ISO9227 NSS), temperature test, tensile test (DIN EN10002), pressure cycling test, and burst pressure test need to be included in guidelines[36]. Moreover, quality assurance by the contractor to track the leak occurrence should be incorporated in the new codes[3].

The third identified need for a leak tight RACHP system is developing and utilizing alternative joining methods and materials. It may include developing and adopting hybrid joining connections (combining torque fitting with non-mechanical joining), fiber laser welding system, nanotechnology multilayer electro joining, lower temperature joining techniques, and developing self-sealing joints fittings and components. It also includes incorporating advanced materials that reduce the number of internal joints and next-generation leak detection systems[25].

Moreover, braze joint sealing technology, improvements in brazing quality through micro-engineered surface structures, and surface modification can reduce brazing joint leak by 25% and total leak from 4% to 3% in rooftop chillers[32]. Some of the existing joining methods have been proved to provide more leak tight-fitting than others, indicating their proper use in specific applications. Hence these methods should be preferred. For instance, press-connect fitting (O-ring fitting) is proposed as an alternative to brazing to create a more leak-free seal, as stated in the findings of this study in the previous section. It has been proven reliable in plumbing applications and RACHP systems and is compatible with the common refrigerants commonly used today, such as R134a, R410A, and R404A[4].

Besides, avoiding use of the brazing method in joining high-pressure tubes, mainly when the building is open to the public, avoiding brazing aluminum tubes, and using crimp fitting in such applications can reduce the leaks. When using crimp fitting, the deformation of tube ends due to axial loads and internal pressure needs to be avoided to achieve a leakless connection[33]. Moreover, flare and compression fitting are used with vibration, harshness, brazing, and press fittings in freezing and thawing situations[27].

5. Conclusions and Future Work

This study found that, among the various system-level vulnerable leakage areas in RACHP systems, flare fitting, mechanical fitting, and brazed fitting connections are the most common leak sources as witnessed by technicians and operators of RACHP businesses in Malaysia. This result is consistent with other international studies on leak sources in commercial systems. In addition, the study categorized leak prevention solutions in three broad pathways: (1) adherence to the best practices by the technician personnel and operator of the RACHP equipment in every single stage of servicing and maintenance involving installation, maintenance, repair, and decommissioning of the system; (2) strengthening existing standards particularly standards relevant to leak testing and leakage prevention; and (3) research, development, and utilization of new joining materials and alternative methods in RACHP industry such as hybrid joining that combine torque-based fitting with secondary non-mechanical joining technique, fiber laser welding system, and reactive nano-technology multilayer electro-joining techniques for leak tight connections in RACHP system. These three pathways will ensure a leak tight system that greatly reduce the TEWI of the system as well as guarantee significant amount of energy savings in the system.

The findings of this study show consistency with other international studies on sources and causes of refrigerant leakage, despite limitations in the study. The most important limitation is that stakeholders (the RACHP equipment manufacturers and service contractors, etc.) are usually uncomfortable with acknowledging their systems leak, especially if they involve ozone depleting and high global warming potential gases (HCFCs and HFCs), thus affecting the validity of survey result at some extent. Additionally, data extraction on actual leaks is time-consuming and costly, potentially leading to extended down-time of systems under repair and maintenance. The findings about leak prevention solutions, however, are very inclusive and their applicability can be generalized not only in the Malaysian context, but to all developing/emerging countries that lack regulations in the RACHP industry and fluorocarbon management.

The study results are of significant importantance for the management of fluorocarbon gases in Malaysia and developing/emerging countries as a whole. The study provides knowledge on leakage sources in RACHP systems, which is critical for the optimization, monitoring, and maintenance of systems to reduce significant amounts of direct and indirect GHGs emissions and promote energy savings in the RACHP industry. In addition, the study proposes insightful pathways for leakage prevention, especially in those legislative and regulatory areas related to monitoring, optimization, and maintenance of RACHP systems. The study findings can be used by the government and policy makers to identify the regulatory gaps and enforce regulations related to the RACHP industry accordingly. The findings can be particularly insightful in the context of cooling efficiency improvement and fluorocarbon management programs.

Future works may cover a broader investigation of leakages through surveys by including equipment users in the survey besides industry stakeholder companies and RACHP operators. Moreover, an extensive experimental study of leaks for various system types is needed to validate the survey results and accurately determine annual leak amount and increased energy consumption due to those leaks. In addition, further study is needed to accurately determine a correlation between refrigerant leakage and energy consumption for various types of RACHP equipment to determine the energy saving potential from leakage prevention.

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Asia project.

Nomenclature

COP	coefficient of performance
GHG	greenhouse gases
HFC	hydrofluorocarbons
HVAC&R	heating, ventilation, air conditioning, and refrigeration
RACHP	Refrigeration, Air-conditioning, and Heat Pump Systems
TEWI	total equivalent warming impact
CFCs	Chlorofluorocarbons
HCFCs	Hydrochlorofluorocarbons
JRAIA	Japan's Refrigeration and Airconditioning Industry Association

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