SAFETY FEATURES OF HC REFRIGERANTS IN CAR AIR CONDITIONING

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Abstract

Hydrocarbon (HC) refrigerants are environmentaly safe, readily available, non toxic, and have good thermodynamic and transfer properties. However, they are also flammable. The subject of this paper is the effect of leakage of refrigerant into the passenger compartment of a vehicle from an assumed fracture in the refrigerant circuit. If the resultant mixture in the passenger compartment is close to stoichiometric, it can be ignited and create sufficient overpressure to damage structures. The result of the research described in this paper is a set of requirements necessary to avoid this scenario.

keywords: *hydrocarbons, accident scenario, refrigerant leaks, system modelling*

Notation

A_A	external surface area $\left[m^2\right]$
a	speed of sound $\left[\frac{m}{s}\right]$
c_p	isobaric specific heat capacity $\left[\frac{J}{kgK}\right]$
c_v	isochoric specific heat capacity $\left[\frac{J}{kgK}\right]$
D	hydraulic mean diameter [m]
f	friction factor
$H_{1,2}$	effective radiation area $\left[m^2\right]$
h_c	comb. heat transfer coefficient $\left[\frac{W}{m^2K}\right]$
h_{fg}	latent heat of vaporizaton $\left[\frac{J}{kg}\right]$
h	specific enthalpy $\left[\frac{J}{kg}\right]$
L_c	critical hose length [m]
L	hose length [m]
M	Mach number
m	mass [kg]
$\dot{m}$	mass flow rate $\left[\frac{kg}{m^2s}\right]$
p_a	atmospheric pressure [Pa]
p_b	back pressure [Pa]
p	static pressure [Pa]
Q	heat [J]
$\dot{Q}$	heat rate per unit time [W]
R	characteristic gas constant $\left[\frac{J}{kgK}\right]$
T	absolute temperature [K]
t	temperature [°C]
V	velocity of the fluid $\left[\frac{m}{s}\right]$
v	specific volume $\left[\frac{m^3}{kg}\right]$

Subscripts

A	system (accumulator)
c	critical
e	environment
R	refrigerant
o	stagnation condition
1	state at section 1
2	state at section 2

Superscripts

*	conditions at M=1
•	rate of change in time

Abbreviation

CFCs	chlorofluorocarbons
COP	coefficient of performance
GWP	global warming potential
HC	hydrocarbons
HFC	hydrofluorocarbons
LPG	liquefied petroleum gasses
ODP	ozone depletion potential

Greek symbols

ε	emissivity
γ	ratio of isobaric and isochoric specific heat capacities
ρ	density
σ^*	Stefan-Boltzmann constant

1 Hydrocarbon refrigerants' revival

The phase out of chlorofluorocarbons (CFCs) and mounting evidence on the unacceptably high global warming effect of their proposed replacement hydrofluorocarbons (HFCs), has opened the path for the return of hydrocarbon (HC) refrigerants. Liquefied Petroleum Gasses (LPGs) were first used as refrigerants in the 1920's, but were kept out of the market because of their flammability. Lack of a satisfactory replacement for CFCs has forced us to reconsider how dangerous their flammability actually is.

Revival of HC refrigerants started in 1989, at the Institute of Hygiene in Dortmund, Germany. The young and enthusiastic director, Dr Harry Rosin used a mixture of propane and isobutane for the Institute's new cold storage room. After that, with the help of Greenpeace, he managed to expand usage of HCs to domestic refrigerators. Today, HCs are widely used in large industrial facilities and, as their behaviour in smaller systems is being mapped and necessary safety measures determined, they are becoming increasingly popular in general refrigeration and air conditioning applications.

Experience has verified a mixture comprising of 50% isobutane (R600a) and 50% propane (R290) by mass, as a 'drop in' replacement for R12. In this paper that mixture shall be referred to as R-290/600a.

As far as good refrigerant properties are concerned, R600a is the driving element in this mixture. Table 1.1 provides a comparison of some of the physical, thermal, transport and environmental properties of R12, R134a and R-290/600a:

PROPERTY		R-12	R-134a	R-290/600a
1.	Chemical classification	CFC	HFC	HC
2.	Molar mass [g/mol]	120.93	102.0	51.115
3.	Normal Boiling Point at 101.325 kPa [°C]	-29.79	-26.16	-33.35
4.	Freezing Point [°C]	-158	-96.6	-74
5.	Critical Pressure [kPa]	4113	4067	3518
6.	Critical Temperature [°C]	112	101.1	108.53
7.	Specific Heat of Saturated Liquid at 30°C [kJ/kgK]	0.998	1.447	2.54
8.	Specific Heat of Saturated Vapour at 30°C [kJ/kgK]	0.721	1.044	1.7
9.	Density of Saturated Liquid at 30°C [kg/m^3]	1292.5	1187.2	515.73
10.	Density of Saturated Vapour at 101.325 kPa [kg/m$^{3]}$	6.3	5.26	2.557
11.	Latent Heat of Vaporisation at 101.325 kPa [kJ/kg]	165.9	216.83	410.3
12.	Thermal Cond. of Saturated Liquid 30°C [W/mK]	0.0698	0.0842	0.1073
13.	Thermal Cond. of Saturated Vapour at 30°C [W/mK]	0.01034	0.0146	0.0184
14.	Viscosity of Saturated Liquid at 30°C [μ Pa.s]	189.1	200.7	109.9
15.	Viscosity of Saturated Vapour at 30°C [μPa.s]	13.7	12.48	8.32
16.	30°C Saturated Liquid k/μ [kJ/kgK]	0.369	0.419	0.976
17.	Temperature Glide [°C]	0	0	7.5
18.	Atmospheric life [years]	130	16	<1
19.	Global Warming Potential [100 years basis]	7300	1200	8
20.	Ozone depletion potential [R12]	1	0	0

Table 1.1
Comparison of basic refrigerant properties

Except for the obvious better environmental properties, R-290/600a shows better thermal and transport properties. Field trials in car air conditioners have shown a 10% increase in refrigerating capacity with R-290/600a over R12. They have also indicated that R-290/600a is completely soluble in and compatible with hydrocarbon lubricants used with R12 (Gomma 1995). From this point of view, no additional measures need to be taken when a car air conditioning system is being converted from R12 to R-290/600a.

2 Accident scenarios

Air mixtures containing 1.95% to 9.1% by volume, of R-290/600a are flammable at atmospheric pressure. A concentration of 1.95% by volume shall prove important in further discussion, and shall be referred to as the *Lower Explosion Limit* (LEL).

The decision of the US EPA (June 1995), prohibited use of HC refrigerants as a substitute for R12 in all end-uses other than industrial process refrigeration. A similar ban was introduced (October 1996) by NSW State Government. This means that, in US and NSW, R-290/600a may not be used as a substitute for R12 in automobiles. The US EPA showed concerns about the safety of using a flammable refrigerant in a system not designed to reduce the risk posed by flammability. It required that any submitter of a flammable substitute refrigerant conduct a scientifically valid, comprehensive risk assessment. So far no such assessment has been submitted.

A scenario which could prove the use of HC refrigerants in car air conditioners dangerous, is 'the bomb in the passenger compartment' scenario. A section of the car air conditioning system is located within the passenger compartment, behind the dashboard. In this scenario a fracture in that section is somehow expected to occur, through which all the refrigerant from the system would enter the passenger compartment and form a flammable mixture. Winding down a window would create a safe situation in a few seconds. However, this scenario assumes that everyone ignores the white cloud coming from under the dashboard. An ignition source is then expected to occur before refrigerant concentration drops below LEL. The period of time in which the HC concentration is above LEL shall be referred to as the *flammable time*. If ignition occurs, the passenger compartment will pressurise, and the car windows will blow out. LPG explosive accidents with domestic appliances show that occupants' exposed skin would become red and sting for a few days (Maclaine-cross, Leonardi 1995). If the car was in motion during the accident, the damage could be substantial due to the driver’s possible loss of control over the vehicle.

The following events are necessary for the development of the above scenario:

1. A leaking fracture has to occur in the refrigerant line within the passenger compartment
2. A flammable mixture has to be formed
3. An ignition source (eg burning match) has to occur

2.1 Fractures and failures in the refrigerant circuit

Despite high level of leakage from car air conditioners (mainly through rubber hoses and O rings), in general, failures and fractures in the section within the passenger compartment are very rare. They may occur as:

- fatigue fractures,

- complete and instantaneous ruptures during collisions,
- fractures during collisions,
- O ring failures

In a system with a multitude of moving parts, fatigue fractures are not an oddity. Although they do not seem to appear in the section of car air conditioning system within the passenger compartment, they have to be considered as the most likely source of dangerous fractures.

High speed collisions may cause deformation and complete rupture of the car air conditioning system. However, it is much more probable that the rupture will occur in the section of the air conditioning system located within the engine bay, than in the section sheltered within the passenger compartment. If the collision was violent enough, glass shattering is much more probable to occur before the rupture of air conditioning piping, and without glass on the vehicle, ventilation rates are too high for flammable mixture to occur.

Low speed collisions may cause a fault in the refrigerant piping to develop into a fracture and leak undetected.

O rings are not used within the passenger compartment, and may appear there only as a part of very crude, dealer-installed air conditioning system.

2.2 Ignition sources

Razmovski (1994) and Rjasekariah (1995) searched for ignition sources in the parked car, with the motor running , using a propane welding torch attached to a cylinder of HC refrigerant. The torch was ignited, and then extinguished with an air blast, and tested for easy ignition with lighted matches. The extinguished torch was played over the hot engine, electrical cabling, ignition, exhaust, fan motor, light and brake switches, relays and cigarette lighter. No ignition sources were found. Therefore, the only remaining relevant ignition sources are matches and butane lighters.

2.3 Refrigerant charges and ventilation rates

A very important factor in establishing the maximum HC refrigerant concentration in a passenger compartment is system refrigerant charge. At the beginning of the research in this field at the UNSW, car air conditioning systems were constantly overcharged (Abboud 1994, Gomma 1995) because researchers relied on the sight glass while charging the system. Finally, 35-40% by mass of recommended R12 charge has been established as an optimum. Refrigerant charges used in calculations in this paper are 35% of the R12 charge recommended by Victorian Automobile Chamber of Commerce.

Razmovski (1994) and Rjasekariah (1995) measured ventilation rates and passenger compartment volumes for several Australian car models using carbon dioxide as a tracer. Vehicles were parked in a sheltered outdoor position so that ventilation rates were as low as possible. The additional pressure difference due to the dynamic pressure in a moving vehicle would increase these rates. Measurements were conducted with:

- a vehicle with all the windows closed and fan not operating
- a vehicle with all the windows closed and fan operating

Model name & year of manuf.		Volume [m^3]	Fan off [l/s]	Fan on [l/s]	Refrig. charge [g]
Magna	1989	6.12	6.00	100.7	245
Commodore	1979	3.81	5.78	85.0	440
Falcon	1987	4.44	38.30	134.5	455
Pulsar	1984	4.16	0.61	77.4	350

***Table 2.1*:**
Passenger compartment volume, ventilation rates and HC refrigerant charge for several typical Australian car models

Winding down a window doubled and tripled ventilation rates, and opening the door for 3 seconds caused a loss of about 30% of the tracer. Both events would prevent reaching LEL in any circumstances.

3. Refrigerant systems and leaks

In order to understand 'the bomb in the passenger compartment' scenario, basic features of the car air conditioner have to be explained. In car air conditioning, the type of the throttling device determines the system type. The two basic system types are:

	THROTTLING DEVICE	**STORAGE OF EXCESS REFRIGERANT**
SYSTEM 1	• TX valve	• liquid line receiver-drier
SYSTEM 2	• orifice tube	• suction line accumulator

Since car air conditioners have a high level of leakage and hose effusion, they are usually overcharged to compensate for refrigerant losses. The storage device for the excess refrigerant is determined by the selection of the throttling device. A system containing an orifice tube that cannot halt refrigerant flow, requires a suction line accumulator. It prevents penetration of liquid refrigerant into the compressor, accommodates refrigerant overcharge and houses desiccant and filter. With a TX valve there is no need for this kind of compressor protection, and the receiver drier is located in the liquid line. This device contains about 0.5 l of excess refrigerant. Figure 3.1 shows the basic components of ‘SYSTEM 1’ and their position.

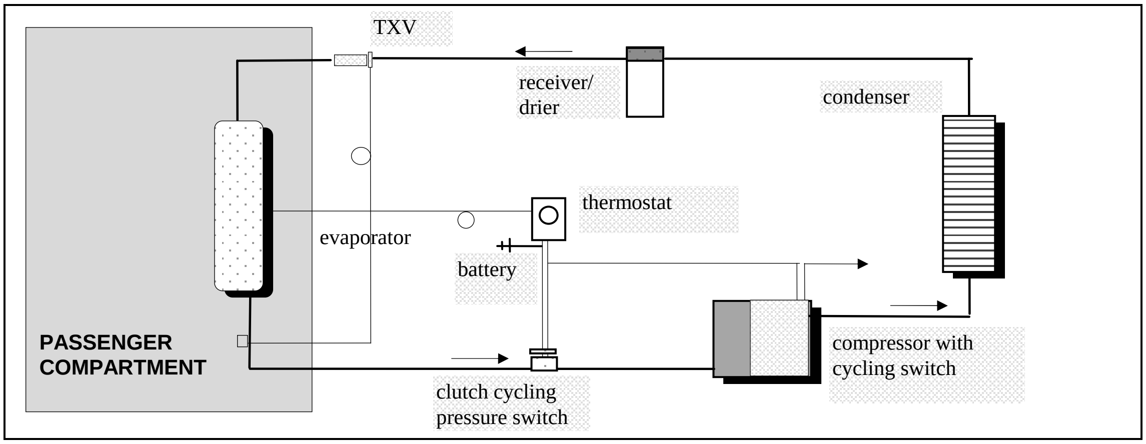

Figure 3.1: Components of car air conditioner SYSTEM 1 (receiver drier/TX valve)

The system shown in fig. 3.1, has become a standard in the Australian automotive industry of today. The alternative to ‘SYSTEM 1’ is ‘SYSTEM 2' shown in fig 3.2, which has become very rare in modern cars.

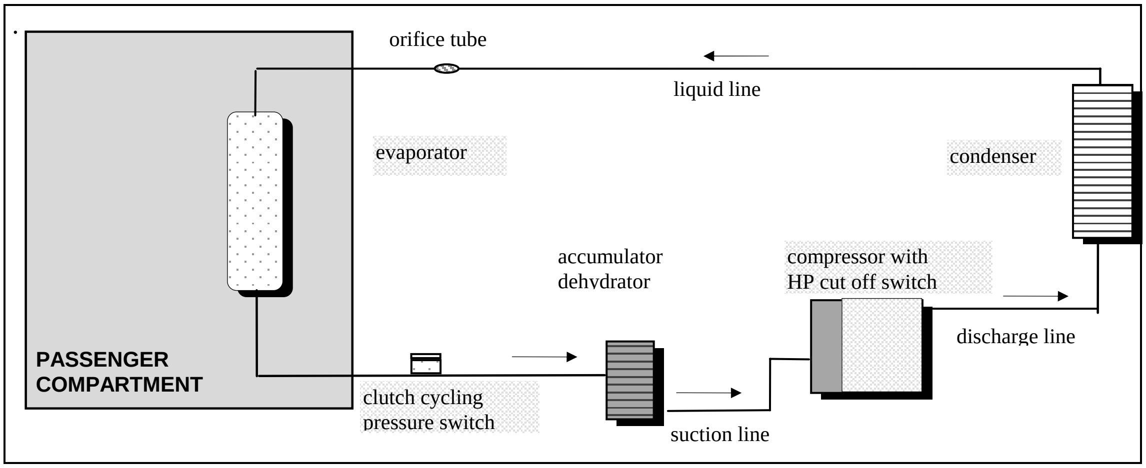

Figure 3.2: Components of car air conditioner SYSTEM 2 (accumulator/orifice tube)

3.1 Systems with an orifice tube and suction line accumulator

Figure 3.2 shows that the release of refrigerant into the passenger compartment with ‘SYSTEM 2’ is possible only if a fracture occurs in the evaporator or in the section of suction line within the compartment. The orifice tube, connecting the liquid line and the evaporator in this type of system, starts in the engine bay. Therefore, a fracture in the liquid line cannot deliver any refrigerant into the passenger compartment. Having taken all this into account, the system with a suction line accumulator/orifice tube appears to be more dangerous. This is because of the excess refrigerant located in the suction line, having direct access to the evaporator and subsequently, to the passenger compartment.

With vapour line fracture, when pressure is suddenly released all the refrigerant from the evaporator almost instantaneously enters the passenger compartment. Refrigerant from the suction line accumulator starts to flash, due the sudden pressure drop, and gaseous refrigerant rushes, through the hose connecting the suction line accumulator and evaporator fracture, into the passenger compartment. Flow through the orifice tube is choked and does not exceed the normal system refrigerant flow rate, having a very small influence on the process. Several major factors, influencing the flashing process, may limit the quantity of the discharged refrigerant. These include:

- Fracture size
- Heat transfer rate to the refrigerant
- Desiccant and oil in the suction line accumulator

Refrigerant mass flow rate through the fracture increases with the increase in the fracture size. Also, certain heat flow to the refrigerant is required to fuel the flashing process. If this is not provided , the refrigerant may even freeze up while flashing. Oil in the refrigerant and the desiccant in the accumulator may also slow flashing.

In order to obtain an actual leakage rate, a computer model based on Compressible Flow in one dimension and Heat Transfer theory has been made, and its validity checked by experiments in which refrigerant was released from the suction line accumulator through the hose which connects it to the evaporator. Experiments were necessary to check the influence of the factors too complex for modeling (oil influence) or related to unreliable data (desiccant influence) on the process.

The main source of refrigerant, in this case, is suction line accumulator. It may be treated as a pressure vessel containing compressible fluid, discharging it through the hose into the environment. Observed in infinitesimal periods of time dt, the system may be treated as quasi-stationary. The fracture was assumed to be circular shape.

Based on these assumptions, a model described in Appendix A has been created. The model has been used to write a program simulating the process (Tosovic 1996). Refrigerant used in the program was 50% propane, 50% isobutane, by mass. The accumulator refrigerant charge was assumed to be 250-300 g.

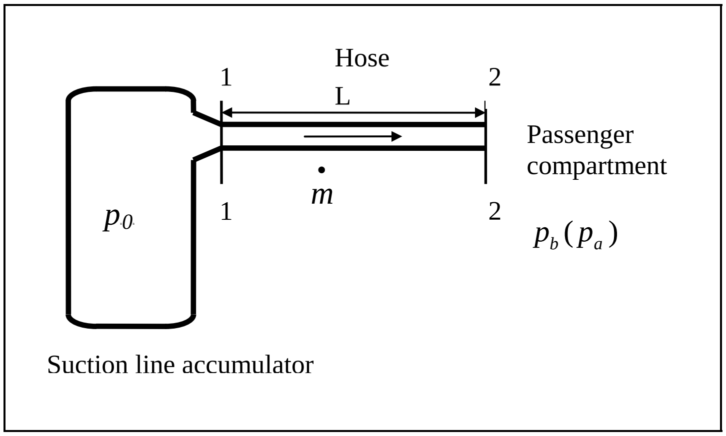

Figure 3.3: Suction line accumulator discharging into passenger compartment

The program predicted that flashing of about 55% of the refrigerant is necessary to cool down the accumulator and the remainder of the refrigerant in it to about -33°C, which is necessary to drop the refrigerant saturation pressure to about 101.3 kPa and practically stop the discharge. Apart from the venilation rates, peak concentration of the refrigerant in the passenger compartment and flammable time appeared to depend only on the fracture size and thermal capacity of the system, which determined refrigerant discharge rate. If the refrigerant was stored in the system with a larger thermal capacity more of it would have to flash to cool the system down to required temperature.

Experiments, in which actual car air conditioner parts were used, with HC refrigerant whose composition was identical to the one used in modeling, showed that:

- both desiccant and oil from the system had no noticeable influence on the process development.
- the program produced excellent predictions (1-5% difference in accumulated discharged mass at several control points) for small fractures (up to 3 mm). For larger fractures and the complete rupture a significant difference was observed, due to the fact that flashing vapour instantaneously pushed the remainder of the liquid refrigerant out of the system. This refrigerant wastefully evaporated in the open air producing no reduction in the system temperature. Oil contained in the system was pushed out together with the liquid refrigerant, producing no effect on the process development.

Fig. 3.4 shows the comparison of the experimental results and program predictions for a part of one of the experiments, conducted in order to test the model and the program.

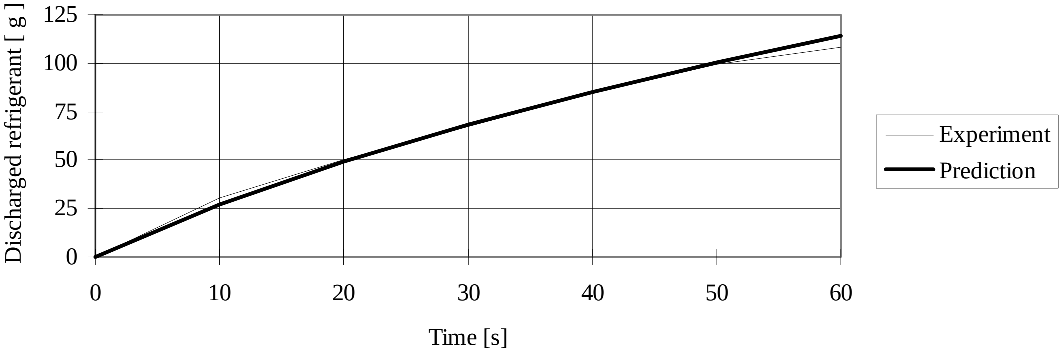

Figure 3.4 1.5 mm Fracture: *Experimental result-Theoretical prediction* comparison

As mentioned earlier, 'SYSTEM 2' is very rare in modern cars. Only one model among those examined, the 1979 Holden Commodore, had this type of system, and even for this vehicle it has been replaced in more recent models. Fig 3.5 shows refrigerant concentration change in the passenger compartment for this car model.

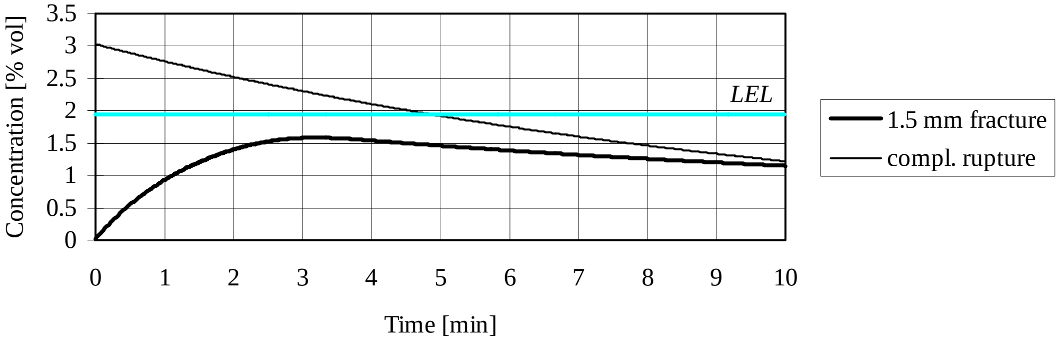

Figure 3.5 Concentration level change in passenger compartment for Commodore - fan not operating

For minimum ventilation levels (i.e. fan off), the maximum flammable time in the case of complete pipe rupture would be around 4.5 minutes.

The most important conclusions obtained so far is that the refrigerant in a car air conditioner does not freeze while flashing, and that the air conditioning equipment has sufficient thermal capacity to support flashing of most of the refrigerant. Predicted cool-down of the system managed only to slow down the refrigerant discharge, as expected. It was also shown that, for larger fractures, practically all of the refrigerant is forced out of the system in liquid state, almost instantaneously.

3.2 Systems with a TX valve and receiver-drier

Release of the refrigerant into the passenger compartment from this type of system is more complex. If the TX valve is located within the passenger compartment, a fracture of interest may occur both in the liquid and in the vapour line. If the TX valve is within the engine bay, a fracture may occur in the vapour line only.

In order to examine actual system behaviour in both situations, an entire air conditioning system was removed from a car, and set up running in the laboratory (Cai

1996). Refrigerant was released, through the circular nozzle, from both the liquid and the vapour line.

A fracture in the liquid line causes liquid refrigerant to flow into the passenger compartment according to Bernoulli and continuity equations. Unfortunately, flashing that occurs due to the sudden pressure drop in the fracture makes the model based on those equations unreliable. Bubble growth within the fracture itself chokes the flow, so that actual refrigerant mass flow rate is lower than predicted. The complexity of the process occurring in the fracture makes it necessary to rely on the experimental results for establishing the actual flow rates. Experiments showed that, for almost any fracture size in the liquid line, all of the refrigerant may be considered to enter the passenger compartment instantaneously. Experimental results were used to model concentration change for the Magna 1989, which was the only car examined with a TX valve in the passenger compartment.

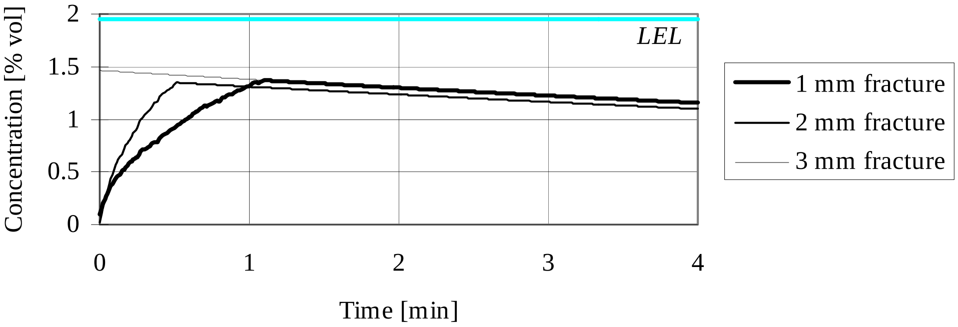

Figure 3.6 Concentration level change in passenger compartment for Magna, fracture in liquid line- fan not operating

The results indicated that the entire refrigerant charge for the Magna was not sufficient to obtain flammable mixture. Therefore, there was no need for further examination of other leakage scenarios for this model.

For this system, the scenario resulting from a fracture in the vapour line is different to one in ‘SYSTEM 2’. Liquid refrigerant can more easily penetrate the TX valve than the orifice tube. When a fracture occurs, all of the vapour line refrigerant enters the passenger compartment. Due to the sudden pressure drop in the vapour line, the pressure difference over TX valve rapidly increases from about 7 kPa to 9 kPa. This leaves the TX valve fully opened and allows all of the liquid line refrigerant to escape, including excess refrigerant from receiver-drier. This is why this system is actually more dangerous than ‘SYSTEM 2’. Though the TX valve is choked most of the time, its influence on refrigerant discharge rate is almost unnoticed through the entire process. Therefore, the model developed previously, describing a pressure vessel containing compressible fluid, can also be applied in this case. Some rectifications had to be made, determining equivalent mass of the system, neglecting friction in hoses etc. The entire air conditioning system was treated as a single pressure vessel, while only the evaporator mass with its enclosure took part in the heat transfer section of the calculations. Experimental results were used to adjust program variables to describe the new system. Following these alternations, high level of agreement between the experimental results and the program output has been achieved. Fig 3.7 compares the two.

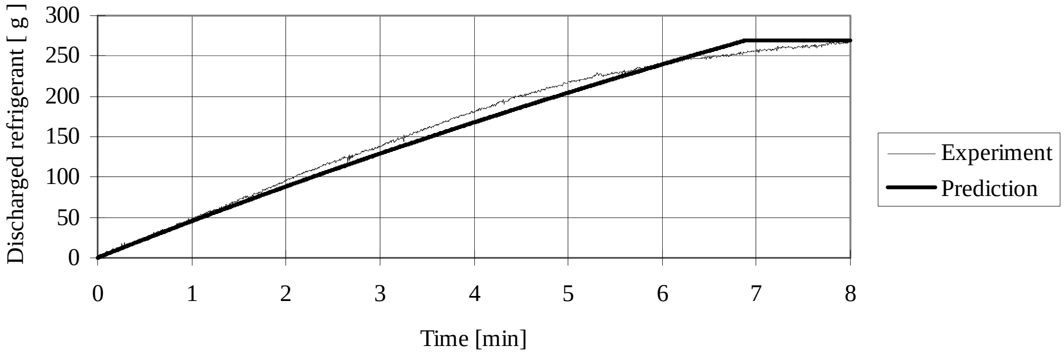

Figure 3.7 1mm Fracture: *Experimental result-Theoretical prediction* comparison

Initially, discharge rates are identical. In the second phase the model overestimates thermal effect, because refrigerant evaporates in other parts of the system, and only vapour reaches the evaporator. When flashing returns primarily to evaporator (liquid coming out of liquid line), discharge rates are identical again. In the final phase, when pressure in the liquid line has dropped sufficiently, the TX valve begins to shut down refrigerant flow, so that the entire process lasts a little longer than expected.

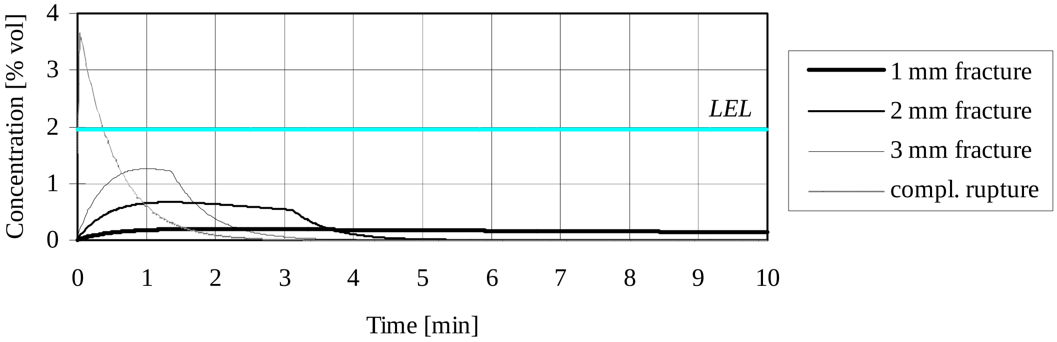

Figure 3.8 Concentration level change in passenger compartment for Falcon - fan operating

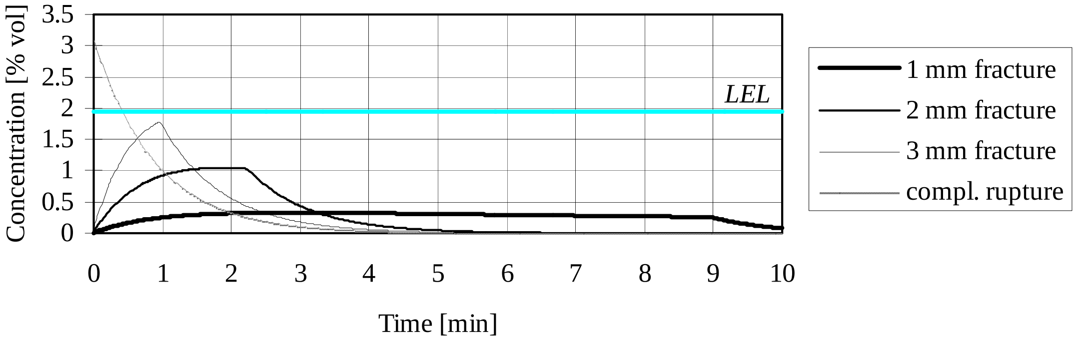

Figure 3.9 Concentration level change in passenger compartment for Pulsar - fan operating

The model has been used to estimate refrigerant concentration change in the passenger compartment of the two remaining examined car models. The TX valve of both models is located in the engine bay, allowing only vapour line discharge into the passenger compartment. Calculations were done both for fan on and off.

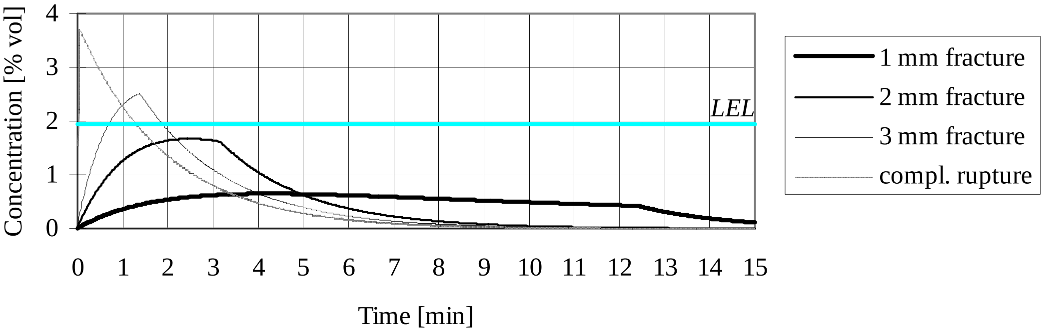

Figure 3.10 Concentration level change in passenger compartment for Falcon - fan not operating

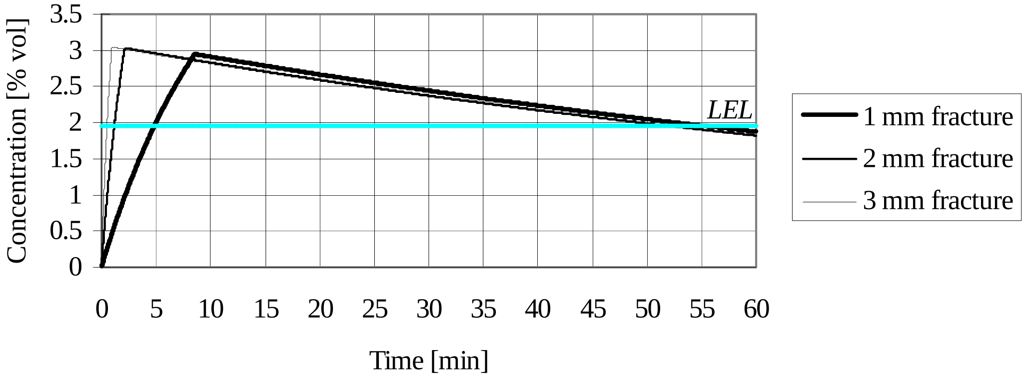

Figure 3.11 Concentration level change in passenger compartment for Pulsar - fan not operating

For both vehicles, at higher ventilation levels (fan operating), LEL was not exceeded for any of the 1-3 mm fractures. For instantaneous release through the complete rupture in evaporator piping, LEL was exceeded for 25-30 s in both models.

For the Falcon, with lower ventilation rates (fan off), LEL was exceeded for about 1.3 minutes for both 3 mm fracture and complete rupture in the evaporator piping.

For the Pulsar, with lower ventilation rates (fan off), LEL was exceeded for about 50 minutes for all types of fracture. This was due to extraordinary low ventilation rates in this car model.

4 Possible safety measures

All the vehicles observed car models (except for Pulsar), in any circumstances, have flammable times below 4.5 minutes. This is the time in which a lighter or a match has to be ignited within the compartment to cause the accident.

If a car model is not already protected from the occurrence of the flammable mixture in the passenger compartment by its design features, additional safety measures may be taken at the time of conversion to HC refrigerant. Safety valves, that close the system off should a major leak in the passenger compartment occur, are an obvious solution. In its code of practice, IAHRA requires utilisation of such valves. Major HC refrigerant distributors are currently developing this device. They are facing serious problem. As previously mentioned, R-290/600a as a 'drop in' replacement for R12, does not require any changes on a car air conditioning system when converted. Installation of additional safety valves would change this situation. They would have to be very cheap and easy to install, to still make the conversion cost attractive.

'SYSTEM 2' would require only one such device in the vapour line, leaving to orifice tube to protect the liquid line path, but 'SYSTEM 1' (almost standard) would require this device in both the liquid and vapour lines. No data on the device's nature, performance and cost is currently available.

5 Conclusion

When all the findings presented are taken into account, it becomes obvious that one singular judgement on the subject of HC refrigerant safety in car air conditioning cannot be made. It may be said that, for some vehicles (Magna), having HC refrigerant in air conditioning system is perfectly safe in any situation. It may be also said that, for other vehicles (Pulsar), in certain circumstances, having HC refrigerant in the car air conditioner may not be safe. The actual judgement depends on the specific model and its design features. The best possible safety measure is adequate car design. Latest Australian vehicles have sufficiently high passenger compartment ventilation rates even when the fan is off. Increased air conditioning system efficiency, resulting in further reduction of the refrigerant charge is highly desirable. A larger passenger compartment volume is also helpful.

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APPENDIX A

(refer to Figure 3.3)

Basic Compressible Flow equations

- Isentropic Flow

$$\frac{p}{p_0} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}} \tag{1}$$

$$\frac{T}{T_0} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \tag{2}$$

- Adiabatic Flow With Friction

$$4f\frac{L_c}{D} = \frac{1}{\gamma}\left(\frac{1}{M^2} - 1\right) - \frac{\gamma + 1}{2\gamma}\ln\left(\frac{2 + (\gamma - 1)M^2}{(\gamma + 1)M^2}\right) \tag{3}$$

$$\frac{p}{p^*} = \frac{1}{M}\sqrt{\frac{1 + \frac{\gamma - 1}{2}}{1 + \frac{\gamma - 1}{2} M^2}} \tag{4}$$

Basic Heat & Mass Transfer equations

$$dQ = dmh_{fg} \tag{5}$$

$$dQ_e = h_c A_A (T_e - T_0) dt \tag{6}$$

$$\overset{\bullet}{Q}_r = \sigma^* \varepsilon H_{1,2}\left(T_e{}^4 - T_0{}^4\right) \tag{7}$$

MODEL

FLOW CLASSIFICATION

Assumption $M_2 = 1$
From equation (3) obtain M_1

$$p_k = p_0 \frac{\left(\frac{p}{p_0}\right)_{M_1}}{\left(\frac{p}{p^*}\right)_{M_1}} \tag{8}$$

- **CHOKED FLOW ~** $p_k \geq p_a$

From equation (2) obtain T_1

Speed of sound:

$$a_1 = \sqrt{\gamma R T_1} \tag{9}$$

Equation of state:

$$\rho_1 = \frac{p_1}{R T_1} \tag{10}$$

Mass flow rate $\overset{\bullet}{m} = A \rho_1 M_1 a_1$ (11)

- **NON CHOKED FLOW ~** $p_k \langle p_a$

using equation (3):

$$\left(4f\frac{L_c}{D}\right) = \left(4f\frac{L_c}{D}\right)_1 - \left(4f\frac{L_c}{D}\right)_2 \tag{12}$$

$$\frac{p_2}{p_0} = \left(\frac{p}{p_0}\right)_{M_1} \frac{\left(\frac{p}{p^*}\right)_{M_2}}{\left(\frac{p}{p^*}\right)_{M_1}} \tag{13}$$

From (12) & (13) obtain M_1 and M_2

Use (2),(9),(10),(11) to obtain $\overset{\bullet}{m}$
For both flow classes:

$$dm = \overset{\bullet}{m} dt \tag{14}$$

HEAT TRANSFER

Using (7),taking radiation in account, combined heat transfer coefficient h_c is obtained.

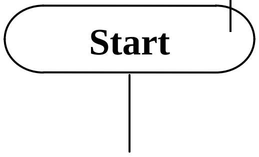
Refrigerant & system temperature change due to flashing:

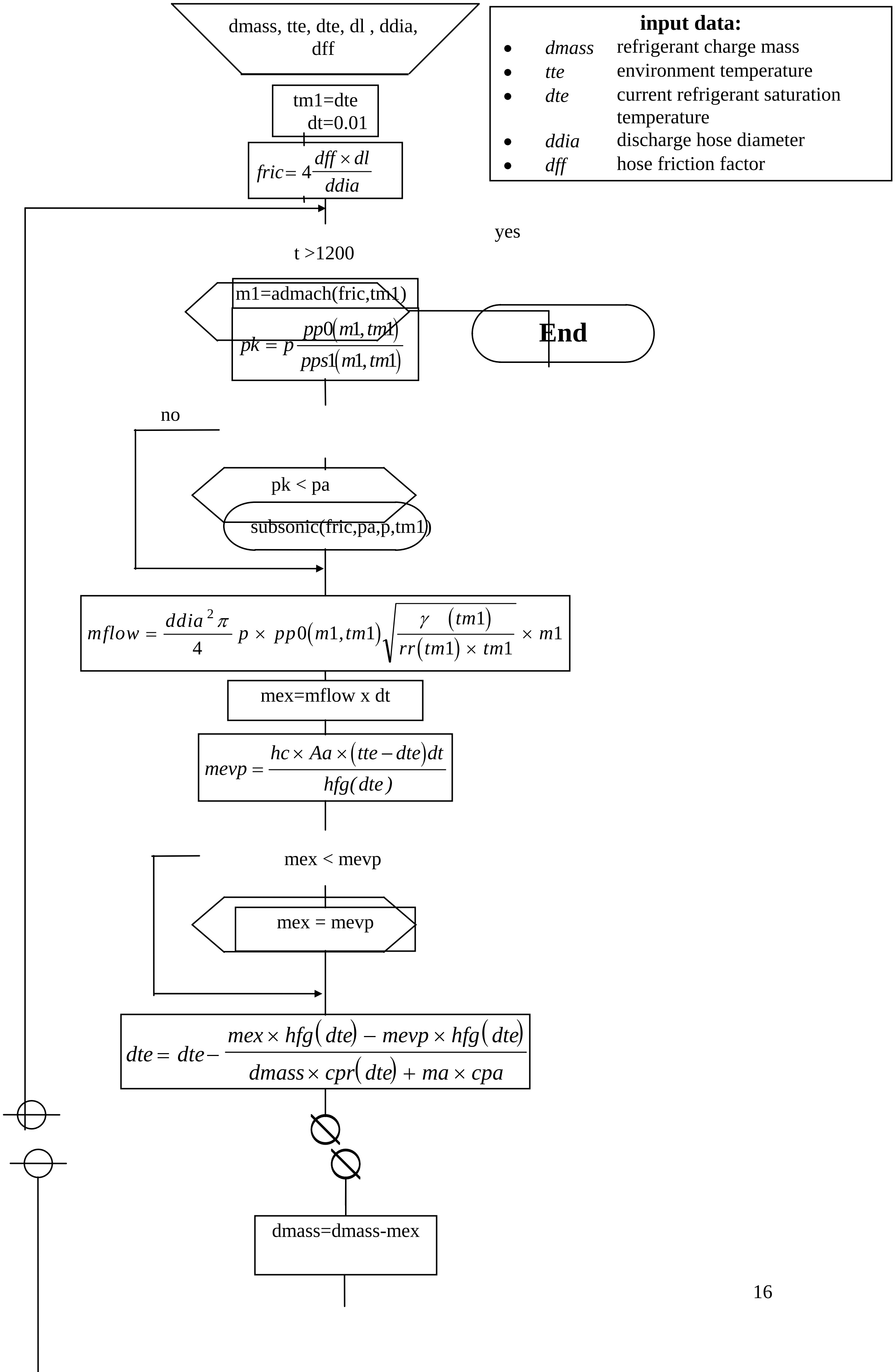
$$dT_0 = \frac{\left(h_c A_A (T_e - T_0) dt - dmh_{fg}\right)}{\left(m_R c_{pR} + m_A c_{pA}\right)} \tag{15}$$

$$T_0 = T_0 + dT_0 \tag{16}$$

If saturation pressure is finally equal to atmospheric obtain dm as:

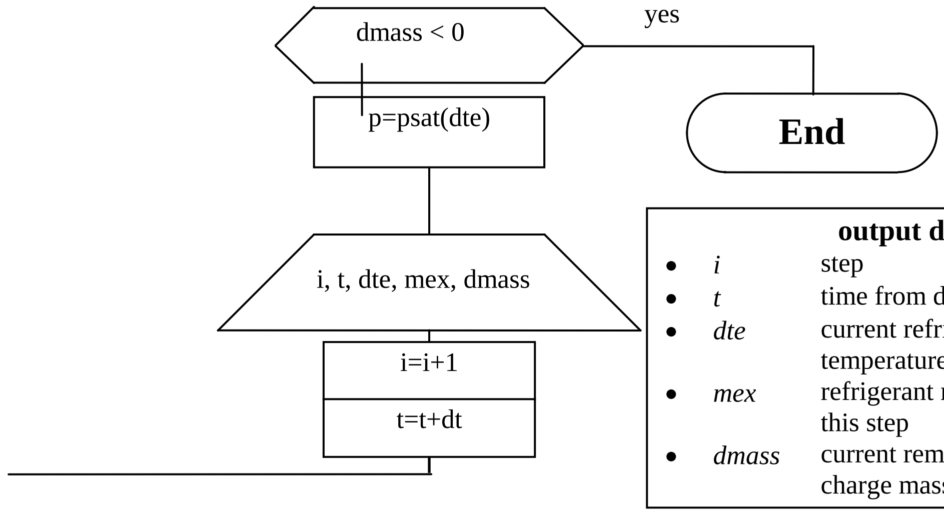
$$dm = \frac{h_c A_A (T_e - T_0) dt}{h_{fg}} \tag{17}$$





input data:

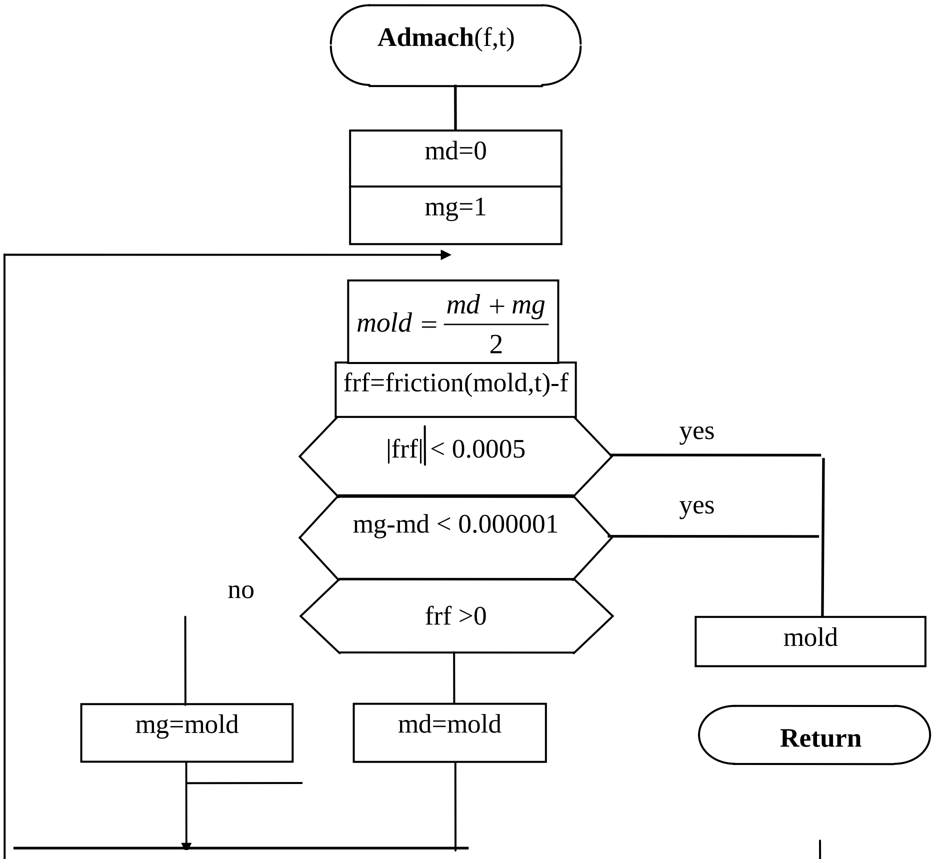
- *dmass* refrigerant charge mass
- *tte* environment temperature
- *dte* current refrigerant saturation temperature
- *ddia* discharge hose diameter
- *dff* hose friction factor



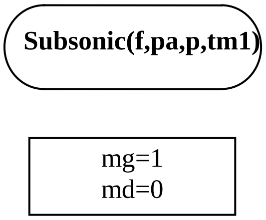
output data:

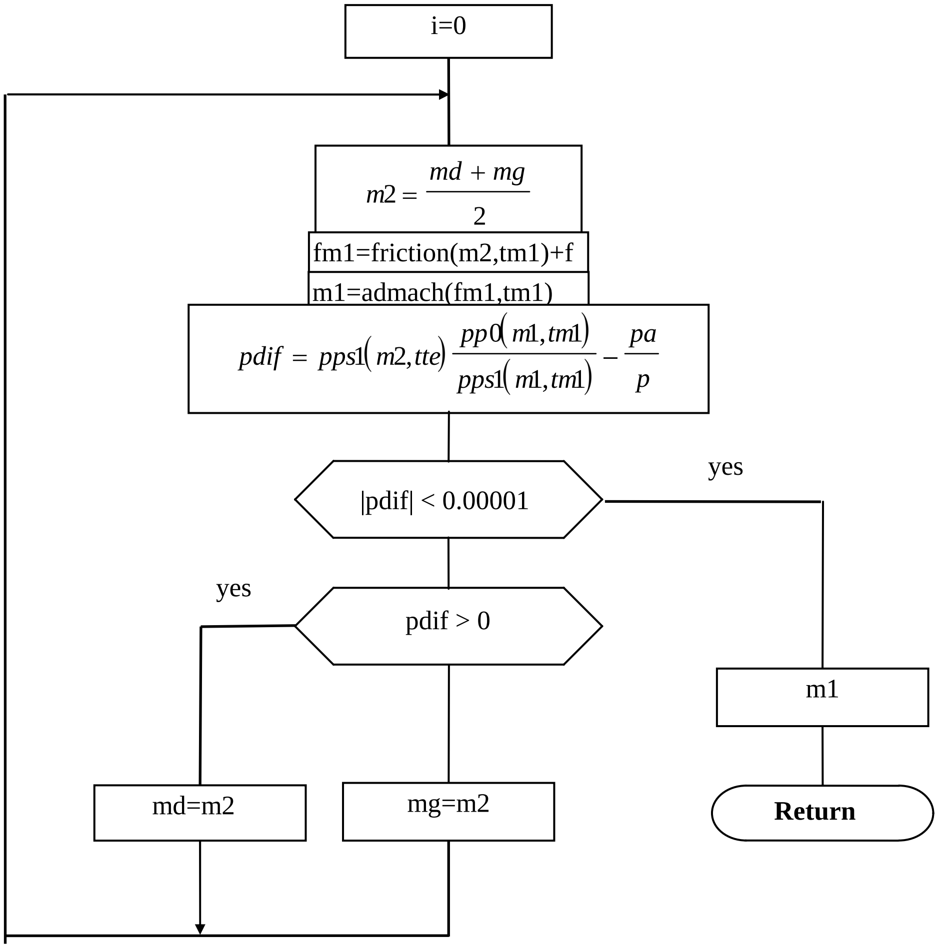
i	step
t	time from discharge initiation
dte	current refrigerant saturation temperature
mex	refrigerant mass discharged in this step
dmass	current remaining refrigerant charge mass

SUBROUTINE ADMACH



SUBROUTINE SUBSONIC





SUBROUTINE FRICTION