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M. Zgliczynski
Aspera

P. Sansalvadore
Aspera

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CONTRIBUTION TO SAFETY ASPECT DISCUSSION ON ISOBUTANE COMPRESSORS FOR DOMESTIC REFRIGERATION

Marek Zgliczynski - Piero Sansalvadore
Aspera-Engineering Dept.
Via Buttigliera, 6 - 10020 Riva presso Chieri TO - Italia

ABSTRACT

Recently use of flammable refrigerants in domestic refrigeration becomes reality in Europe. There are not yet any specific standards for safety approval of compressors for hydrocarbon appliances.

As a contribute to the safety aspect discussion, Aspera performs series of activities to assess the risk coming from use of hydrocarbons in domestic refrigeration.

Basic study on isobutane/air flammability behaviour have been conducted. The effect of use of flammable refrigerants in present hermetic compressors for domestic refrigeration has been experimented. Complete failure mode and effect analysis on product and compressor manufacturing process have been done. Some safety aspects also on complete refrigeration system has been conducted in particular on compressor electrical components safety behaviour.

Having performed above mentioned activities, we can concluded that risk connected with use of hydrocarbon compressors seems to be reasonably low.

1. INTRODUCTION

Recent developments in European refrigeration industry with introduction of hydrocarbons as a refrigerant in domestic appliances can be considered as a kind of revolution.

Public opinion focused by ecologist organizations is paying much more attention to use of environmentally low impact substances. This pressure, especially in German area, went even further than Montreal Protocol limitations. Not only ozone depletion potential but also total global warming effect of substances used in the refrigeration industry is taken into consideration.

Hydrocarbons very well known for years for their excellent thermodynamic properties and very low ambient impact, were always excluded because of their flammability. In practice there was a kind of menthal block not to consider flammable gases for use in the household appliances. In fact very few engineers dedicated their time to study and understand completely the actual risk coming from use of this technology.

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In order to assess this risk Aspera performed, with the help of specialized consultant organizations, a series of activities on isobutane compressor considering also the new EC directive on strict liability where manufacturers are required to produce products as safe as the consumer would aspect them to be. Appliances presently produced with hydrocarbons are designed following the good practice rules, trying to reduce relative risks using protected in-wall evaporators, explosion safe lamps, etc. Not any specific standard is available today. IEC Commitee 61C and National Safety Boards are presently discussing a new standard that extend safety rules to the appliances with hydrocarbons as a working fluid. New IEC standard is expected to be published in 1995.

2. RISK ASSESSMENT CONCEPT

The risk of any event is determined by the product of two elements: probability and effect. The effect means the severity level of the event and the probability means the sensitivity of the event to occur.

In case of reciprocating compressors that use flammable refrigerant, the sensitivity is determined by the possibility to develop flames or create explosions that means creation of combustible mixture and presence of ignition source of enough energy, both inside and outside the hermetic shell.

Summarizing the elements for risk assessment in use of hydrocarbon compressors are the following:

- Creation of explosive mixtures inside the shell
- Creation of explosive mixtures around the shell
- Ignition potential of internal electrical parts
- Ignition potential of external electrical parts
- Severity of internal explosion
- Severity of flame or explosion outside the compressor shell

3. BASIC PROPERTIES OF ISOBUTANE

In order to conduct both severity and sensitivity experimental activity, basic properties of isobutane-air mixture have been evaluated. Series of experiments have been conducted to determine self-flammability of isobutane, flammability limits, maximum explosion pressures and maximum rate of pressure rise.

The oxidation equation governing isobutane reaction is the following (1):

$$C_4H_{10} + 6.5\ O_2 + 24.44\ N_2 \Rightarrow 4\ CO_2 + 5\ H_2O + 24.44\ N_2 \qquad (1)$$

Stoichiometric molar concentration resulting from this reaction is 3.1%. The experiment performed to verify flammability limits, stoichiometric concentration and explosion pressure showed that the max pressure peak occurs at 3,5% isobutane-air mixture (see figure 1) at normal conditions. The maximum explosion pressure condition was experienced also at 6 bar pressure and 80°C temperature (see figure 2). All relevant data are summarized in table 1.

Parameter	**R600a**	**Source**
Relative gas density (air = 1)	2.07	L
Mole weight (kg/kmol)	58.12	L
Vapour pressure at 20°C (bar)	2.1	L
LEL (volume %)	1.7	E
UEL (volume %)	8.5	E
Stoichiometric conc. (volume %)	3.5	E
Δ P max (bar)	7.75	E
Auto-ignition temp.(°C) ASTM E659	455	E

L = Literature

E = Experimental data (99.7% purity isobutane)

Table 1 - Summary of isobutane properties

4. EXPLOSION EXPERIMENTS

The tests were carried out with two specialized institutes. The purpose was to verify directly on the compressors the severity at internal explosion of isobutane-air mixture in the worst stoichiometric conditions and in different situations of temperature and pressure.

The explosion is a very quick burning which creates a final pressure according to a law (2):

$$\frac{P_{max}}{P_i} = \frac{T_{max}}{T_i} \times \frac{n}{m} \qquad (2)$$

where:

P_{max} = final pressure after explosion
P_i = initial pressure
T_{max} = flame temperature
T_i = initial temperature of the mixture
m = molecola number before the explosion
n = molecola number after the explosion

Considering the stoichiometry of the reaction and admitting that was complete, ratio n/m for isobutane is 1.047 (in calculation it will be considered 1).

Knowing T_{max} of the flame, that is for isobutane 2300°K, it is possible (see figure 3) to calculate the theoretical P_{max} of explosion vs. P_i of the mixture and T_i.

Also we have to consider that in the real conditions of the compressors some quantity of oil which will enter in the composition of the mixture decreasing the flame temperature and then P_{max} of the explosion.

4.1 Experimental setup and procedure

The explosion tests on the compressors were conducted with a stoichiometric mixture of isobutane and air introduced into the compressors. The mixture was ignited and the resulting pressure pulse recorded on a fast data logging system.

The following experimental protocol was followed for the tests:

1. The heated compressors were filled with 70°C air to a pressure of 0.6 bar gauge
2. The compressor shell was leak tested
3. 0.1 bar gauge isobutane was added via a separate manifold which did not have any air
4. The balance of pressure requirement was made up with hot air
5. The data logging system was armed
6. The mixture was remotely ignited
7. The explosion products were vented from the compressor shell through the inlet manifold
8. The venting products were ignited to determine whether the mixture had unburnt fuel
9. The compressor shell was vented with fresh air
10. The compressor shell was leak tested to determine whether it had been ruptured by the explosion.

4.2 Experimental results

The table 2 summarizes the results of the explosion tests on 10 compressors in different conditions.

TEST	OIL	TEMP. (°C)	PRESSURE (bar abs)	ISOBUTANE % mol	Δp (bar)
1	Yes	20	1	3.51	3,9
2	No	20	1	3,53	4,2
3	No	20	1	3,49	4,4
4	Yes	20	1	3,54	4,7
5	No	30	2	3,57	16,6
6	Yes	30	2	3,58	15,9
7	Yes	70	5	3,5	27
8	Yes	20	5	3,5	32
9	Yes	70	5	3,5	26
10	Yes	70	5	3,5	27

Table 2 - Compressor explosion - Experimental result summary

The maximum peak of pressure obtained was of 32 bars with 5 bar and 20°C initial conditions. No damage was visible to any of the compressor shells and all the shells held pressure without any leaks after the explosion tests.

The first six samples showed no damage also inside, in fact regularly started after the tests. The last four ones showed internal damages overall in the motor windings: none of these started after the internal explosion.

5. GAS LEAKAGE - PROCESS & PRODUCT FMEA

One of the most important characteristics requested from isobutane compressor is to minimize the probability of leaks. Standard refrigerant compressors have already a very good tightness characteristic due to sophisticated methods used to control the compressor production. Helium leakage test assures today less then 10 ppm field return. This level in comparison with complete system leakage is substantially lower.

To improve this value Aspera conducted failure mode and effect analysis on the product and process in order to reduce the number of leaking compressors shipped to the market. As a result of this activity mainly two improvements in the process have been implemented:

- Helium recheck of repaired compressors
- Not any additional welding operation allowed after helium test

After about one year of production not any leaking compressor was found in the field. For having more significant data, longer observation time is required.

Another important element for evaluation of internal explosion effect is mechanical resistance of the compressor shell.

Present compressor shells have already a very good mechanical resistance in order to assure a sufficient noise attenuation (see figure 4).

If we compare the maximum explosion pressure that reasonably can occur inside the shell, there is a large safety margin also because the mechanical strength to the impulsive load is higher than the static one.

6. IGNITION POTENTIAL OF EXTERNAL ELECTRICAL COMPONENTS

In order to evaluate the risk coming from external compressor electrical component, an experimental activity has been performed with specialized consultant. In the first analysis three elements are able to generate sparks outside the compressor shell:

- Overload protector
- Starting device
- Electrical board and components connections

6.1 Overload protector

Ignition potential of external 3/4" overload has been experimented.
The overload protector was placed in a sealed 6-inch chamber, and a stoichiometric mixture of isobutane and air at atmospheric pressure was introduced.
The switch was connected to a 220-240 V, 60Hz power supply and the data acquisition system/resistive load. A cycle time of approximately 2.5 minutes was observed.
A frangible, thin, mylar disk was used as an explosion indicator. A forced ignition test inside the chamber confirmed that the mylar disk did in fact rupture when an explosion occured inside the chamber.

A calibrated flammable gas detector was used to check the concentration of isobutane in the sealed chamber. As and added precaution, the chamber was completely purged and refilled with a stoichiometric isobutane air mixture every 48 hours.

Two different types of 3/4" overload was tested: one standard with open envelope and the second with protective disk closure (semi-sealed).

Overloads were allowed to cycle for 5000 times. In case of open version explosion occured after 4 overload cycles, in case of semi-sealed version not any explosion was registered during whole test.
In conclusion semi-sealed overload is intrinsically safe for isobutane compressor.

6.2 Starting device

Both PTC and electro-mechanical relay is currently under testing. For the moment only PTC starting device is used in production. The conclusion of these activities will be published in the future.

6.3 Compressor electrical board

Today, with non flammable refrigerant applications, compressor is used as a main electrical connection point of the appliance. Normally certain number of bad connected units is present. There is a potential risk of spark generation or high temperature connections. To reduce this potential risk as a first step we suggest to reduce to the minimum the number of connections present on the compressor board or move the connecting board far from compressor area. This subject requires more investigation in the future.

In any case it is important to assure the sufficient air flow around the compressor shell in order to minimize the probability of explosive mixture permanence.

7. CONCLUSIONS

Present article does not pretend to give a complete answer to the safety issue of using hydrocarbon compressors.
The purpose of the present paper is to share with the engineers involved with this technology Aspera present knowledge in order to contribute for setting correct rules in the future regulations.

In summary we can conclude that compressor shell have enough strength to withstand the internal explosion and extremely low leakage probability.
Small modification in electrical components can eliminate the possibility of spark generation around the compressor shell.
Further investigations are in progress on starting device and electrical connection board.
Final purpose of this research is to assess the risk and compare it with the other risks already present in the normal life.
Considering the present knowledge we can conclude that the risk coming from isobutane compressor seems to be reasonably low.

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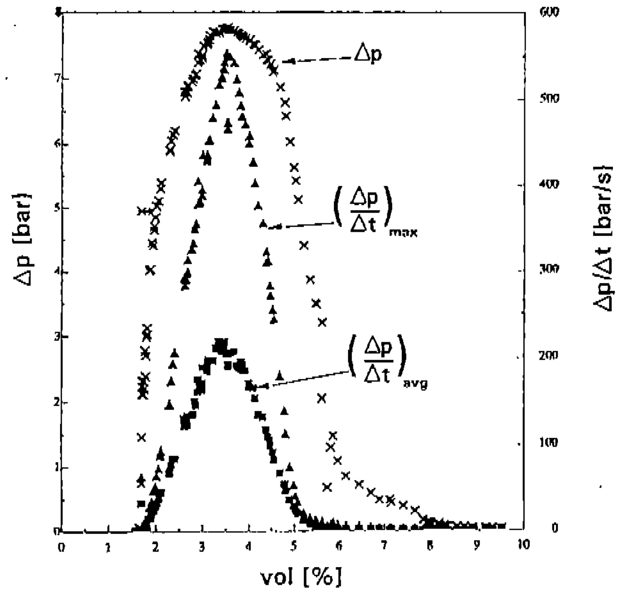

Fig.1: ISOBUTANE - AIR MIXTURE EXPLOSION
AMBIENT CONDITIONS

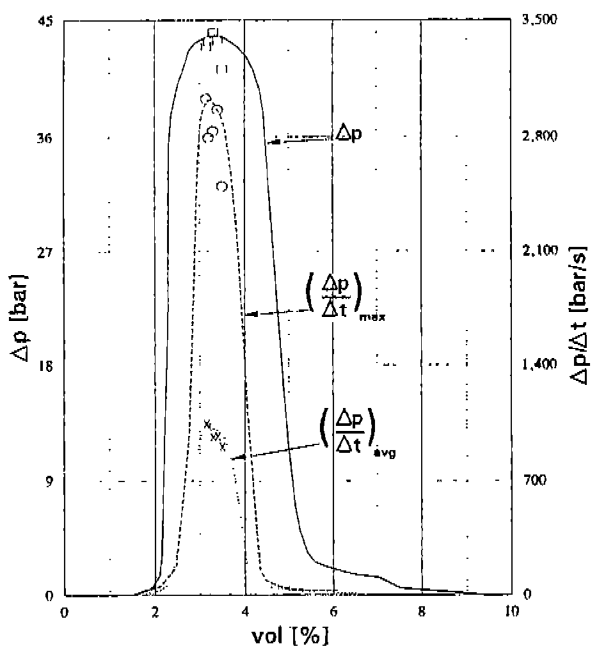

Fig.2: ISOBUTANE - AIR MIXTURE EXPLOSION
@ 6bar abs & 80°C

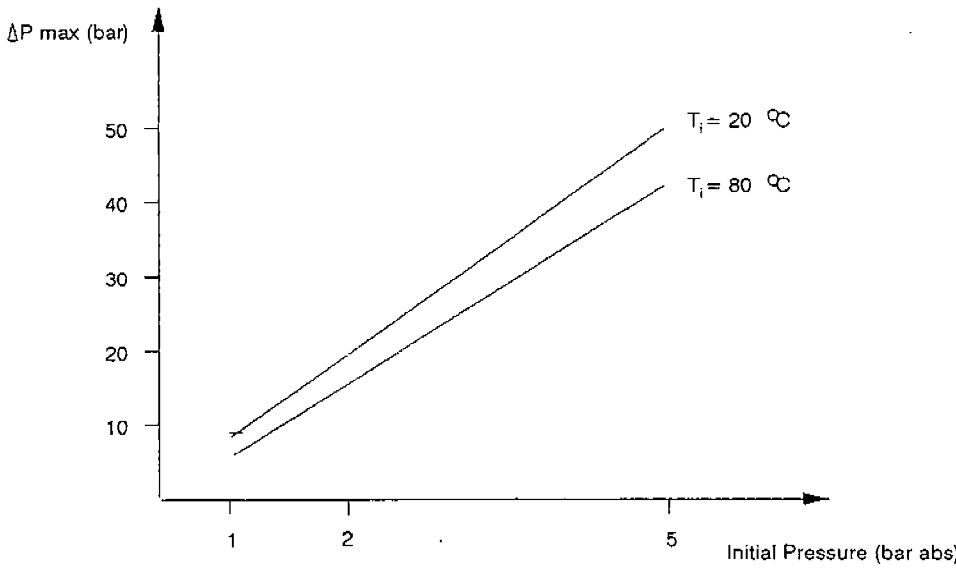

Figure 3 - Theoretical explosion pressure

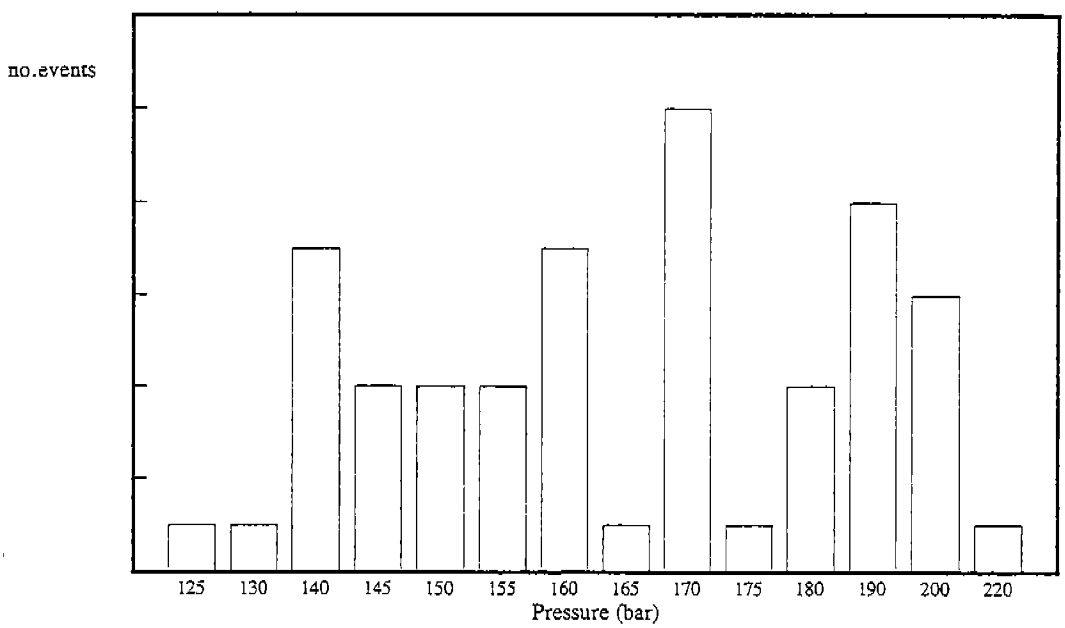

Fig.4 - COMPRESSOR SHELL STRENGTH TEST