



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1071

CONCEPTUAL DESIGN OF AN ADSORPTION REFRIGERATION SYSTEM USING EXHAUST GASES IN TRUCKS

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Abstract.

The core of the technological product innovation is in the concept definition, which needs to be addressed in a convergent way to supplement lack of technological trajectory, lack of resources for testing and laboratories, and encourage networking of researchers.

In this article it is proposed a methodology for concept definition, based on the use of existing test results, and the matrix of contradictions of the inventive methodology TRIZ. The methodology, applied to an adsorption refrigeration system using exhaust gas of automotive vehicles, consists: i) identification and delimitation of the conceptual design phase according, ii) looking for another adsorption refrigeration prototypes and testing in the literature, iii) application of the methodology TRIZ for getting the concept definition.

It should contain neither formulae nor reference to bibliography. The abstract will be included in a printed volume to be distributed to the symposium participants, whilst the full paper will be published in the proceedings.

Keywords: adsorption refrigeration system, exhaust gases, refrigerated trucks

1. INTRODUCTION

The conceptual design phase is the key to the process of technological innovation of product. As soon after identified the necessity and/or problem will need to generate ideas to set up one solution that will reflect in conceptual design. In this intention, the technological surveillance contributes through identifying publications, patents and products already existing in the theme.

There are some publications that evidence links between the process of product development and the conceptual design phase, highlighting the importance of this phase due to its challenges (Lopez *et al*, 2015; Shai *et al*, 2009; Chan & Schunn, 2015; Christensen, 2016).

In this context is proposed a model to improve the conceptual design phase. Therefore, this proposal is applied to the conceptual design of an adsorption refrigeration system that uses the exhausted gases of an automotive vehicle.

In this way, the utilization of the exhausted gas from the automotive vehicles (for cooling) saves energy, while no need to pay the energy to cool. The saving of energy implies the economic saving and consequently will have social impact and in the market.

The adsorption refrigeration system utilizes the heat to activate the refrigeration cycle. Therefore, the heat available in the gas at the exit of the exhaust pipe of the automotive vehicles can be available for cooling.

2. EXPERIMENTAL PROCEDURE

The methodology consists of the formulation of one model to develop the conceptual design of new products, having as inputs:

- i) knowledge obtained from the data of experiments with the prototype (from publications), and
- ii) Application of prioritized inventive principles using the matrix of contradictions of the inventive methodology TRIZ.

After that, this model will be applied to the conceptual design of cooling system by adsorption for foods' transportation trucks.

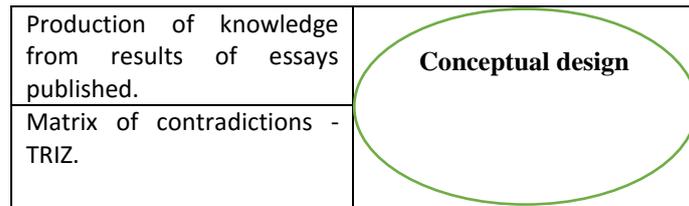


Fig. 1 Model for improve the conceptual design

2.1 Production of knowledge from results of essays published

The methodology proposed, is compatible with Porter & Newman (2011), advocate that is possible to produce knowledge using results of experiments of built prototypes, previously identified. This is in effect, as “to have” the aforementioned prototypes and with the combination of results, generates new knowledge. This proposal implies the dialogue and contact with the sources, according to advocated by Chesbrough *et al* (2005) in Open Innovation. Likewise, seeks to diversify the sources of innovation: users, suppliers and/or industry (von Hippel, 1988). The results of these experiments will be the first input for the conceptual design.

For this, primarily is made a technological surveillance about the topic, identifying publications and patents about it, through research in publications databases as SCOPUS and Science Direct, and software for mapping of patents as Matheo Patent.

As additional result of this knowledge gained, analyzing each essays and prototype, will be possible to find technical contradictions and the forms as them are solved. Having this contradictions identified, will be possible to pass at the following phase, through the use the TRIZ methodology.

2.2 Matrix of contradictions - TRIZ

The TRIZ methodology, which was developed by Altshuller (1988), is based in the induction after the review of millions of the patents arriving to 40 inventive principles, where the contradictions matrix also responds to the same logic.

The matrix of contradictions of the inventive TRIZ methodology (Altshuller, 1988), previously identification of the technical parameters that entering in contradiction during the conceptual design where one of them improves while another gets worse, indicates a group of possible inventive principles TRIZ for solved that contradiction.

The inventive principles determined in this way, will constitute in an input for the conceptual design.

Both sequential inputs will contribute to account for several ideas that are necessary in this stage, to bear the conceptual design.

In this way, it is possible to arrive at a conceptual design in a novel topic and where the trajectory of the research group is still incipient. Arriving at a conceptual design in this way accelerates the process of positioning itself in a certain research topic, where the new research group has still a reduced technological trajectory.

2.3 Conceptual design

Du Prez & Low (2008) present the framework updated for the process of technological innovation. The model is formed by two horizontal and coaxial truncated cones, the first convergent and the second divergent, connected by one block that represents the stage of portfolio of projects. For the authors, the stage of definition of the concept seek “... *to transform the idea into a workable concept. A concept could be developed from different combinations of different ideas. Once a concept has been defined and documented, sometimes should be provided to share the concept to incubate and may refine some of the ideas*”. The stage of conceptual design corresponds with the second compartment of the first cone (convergent) of the model. This stage, preceded by one filter of ideas and by one filter of the concept, is named the definition of the concept, including the components of development of the concept and the incubation and refining of the concept.

To Schnarch (2004) “*the concept of new product is the clear and precise definition, the selected ideas, indicating characteristics, attributes and benefits for certain groups of customers*”.

To bear away the stage of conceptual design are necessary ideas to solve previous problem, the conceptual design. In this stage will be designed the product such that solve the needs of market and/or social implicated.

After the conceptual design phase, continue the prototype development.

3. RESULTS: CONCEPTUAL DESIGN OF A COOLING SYSTEM BY ADSORPTION

Following the integrated methodology proposed, is developed the conceptual design of the adsorption refrigeration system.

3.1 Production of knowledge from results of third part essays

Wang & Oliveira (2006) analyzed an adsorption cooling system, patented by Xia *et al* where water is cooled in the evaporator while methanol extracts heat since outside the tubes where the water to be cooled circulates. Methanol, which evaporates after exchanging heat in the evaporator, then condenses inside the tubes of one of the water evaporators while the other water evaporator collects condensate from the condenser. Thus, the temperature in the second water evaporator will be greater than the temperature in the first water evaporator and in the methanol evaporator.

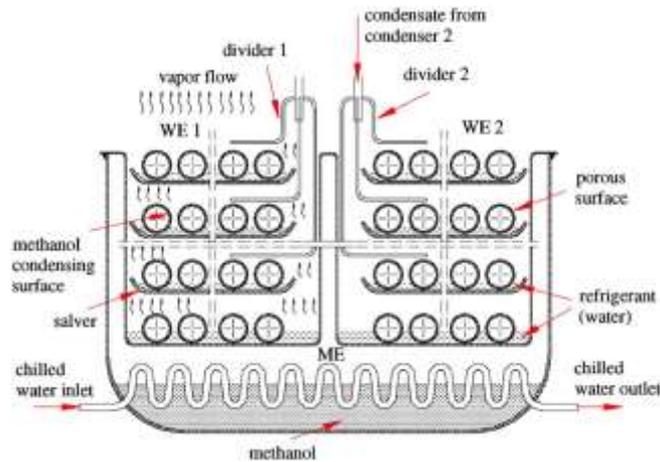


Fig. 2 Adsorption cooling system (Wang & Oliveira, 2006)

Hamdy *et al.* (2005) said that Wang (2008) experimented many adsorption heat pipes, for water chiller or icemaker. In this way, he experimented with two adsorption silica gel – water refrigerators, the first for water cooling getting 0.4 COP with 85 °C and the second for use in a room air conditioner, powered by 80 °C hot water getting a COP more than 0.3.

Wang & Oliveira (2006) adds that in the methanol evaporator, methanol evaporates by capturing heat from the chilled water flow, being collected by a tubes serpentine in the water evaporator, where it is condensed causing evaporation of the refrigerant water, as appear in the Fig. 3

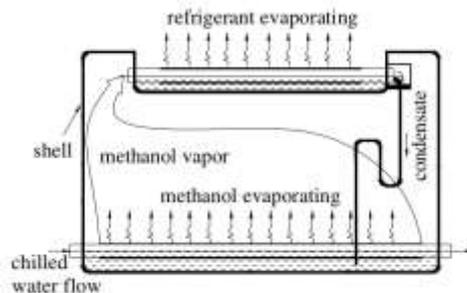


Fig. 3 Diagram of the loop heat-pipe used in the evaporator (Wang & Oliveira, 2006)

Grisel *et al.* (2010) have built one prototype with two adsorbers in parallel, which operate alternatively, where each one supplies a flow of 4 l/min of water. Performed several experiments with the prototype and the formulated mathematical model, allowed to get results.

They constructed their prototype (Fig. 4) using commercial parts and components, so the adsorber was based in a plate-fine evaporator (BEHR, type 33385) that was filled with silica gel, while the condenser and the evaporator consisted of a plate/shell heat exchanger (Vatherus brand).

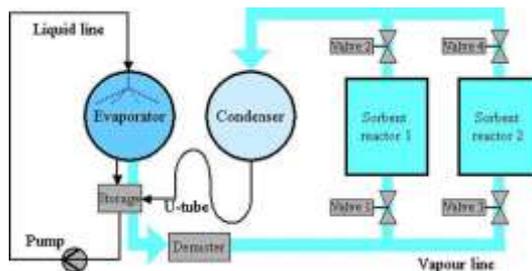


Fig. 4 System layout of the adsorption chiller test facility (Grisel et al, 2010)

Grisel *et al.* (2010) obtained 3.6 kW of cooling power, instead of the expected 5 kW.

This 3.6 kW corresponds with a SCP of 208 W/kg dry silica gel and a standard inlet temperature TH of 87 °C as appear in table I.

TABLE I STANDARD VALUES AND OPERATE CONDITIONS ADSORPTION CHILLER TEST FACILITY

Water circuit	Flow rate l/min (design value)	Standard inlet temperature (°C)	Temperature range for testing (°C)
Heating reactor (s)	16.4 (24.0)	87	73 – 91
Cooling reactor (s)	15.2 (24.0)	25	22 – 43
Cooling condenser	13.8 (12.0)	25	22 – 43
Chilling evaporator	11.0 (12.0)	12	6 – 20

Source: (Grisel et al, 2017)

Hamdy *et al.* (2010) preconize that Wang & Zhang (2009) analyzed a theoretical model using silica - gel and water, getting a COP of 0.5 for a hot water temperature of 85 °C, with a temperature of condenser of 30 °C and chilled water inlet temperature 15 °C.

Wang & Zhang (2009) constructed a prototype (Fig. 5) consisting of two adsorbers, a condenser and an evaporator. The prototype consists of the integration of two sets of tubes with an adsorber at the top, a condenser at the middle and an evaporator at the bottom. Then these tubes are accommodated forming the prototype.

Each tube constituent of the assembly is formed by: i) an adsorber, with its top filled with silica gel and with annular fins by whose axis flows the cooling water. At the top is the process tube through which the refrigerant is charged; ii) a condenser placed immediately below the adsorber and with an isolated space respect the adsorber; and iii) an evaporator in the bottom of the each tube, with thermal isolation respect the condenser.

Already the cooling water flows first from the condenser, and after it is directed to the adsorber.

The evaporator captures heat from the cooling water using methanol as the intermediate heat transfer fluid.

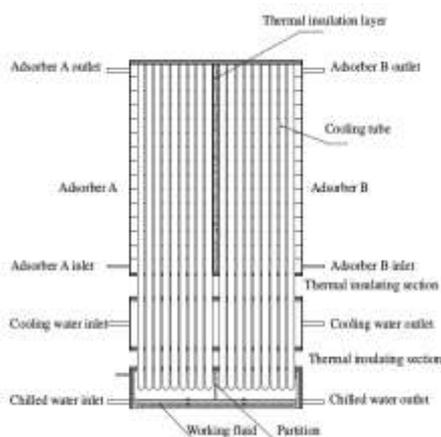


Fig. 5 Adsorption system proposed by Wang & Zhang [18]

Restuccia *et al* (2004) have performed tests on a prototype of adsorption cooling; the same ones that have been compared with a simulation of the same, obtaining similar results. These authors developed a prototype where the heat exchanger is of stainless steel tubes and fins with poor contact between them.

The adsorber consists of an array of eight parallel and connected tubes that have been coated with silica gel with calcium chloride (Fig. 6). This "bed" is placed inside a chamber which is kept empty by a pump and which is communicated with both the evaporator and the condenser by means of two valves.

The experimental results that they obtained ($T_{ev-in} = 10\text{ }^{\circ}\text{C}$, $T_{con-in} = 40\text{ }^{\circ}\text{C}$, $T_{max} = 95\text{ }^{\circ}\text{C}$, $T_{min} = 40\text{ }^{\circ}\text{C}$) were compared with those estimated.

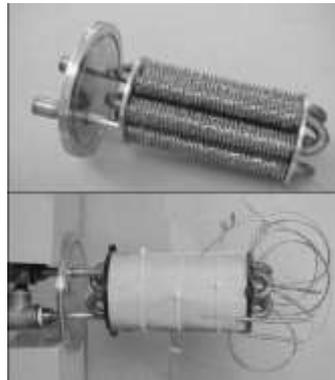


Fig. 6 Adsorber before and after be filled with silica-gel (Restuccia *et al*, 2004)

Núñez *et al* (2004) developed a prototype of adsorption refrigeration, which consist of two identical modules with two exchangers, where one of them behaves as an adsorber while the other behaves as an evaporator or a condenser. Both modules are connected inside a vacuum chamber, linked to the exterior only through pipes. The adsorber heat exchanger is filled with silica gel.

A hydraulic switch connects both modules. Each module is filled with 35 kg of silica gel.

The two modules act in a synchronized way, so while one module is in the adsorption phase the other is in desorption phase, which implies four consecutive operations in the four exchangers.

Núñez *et al* (2007) add that their prototype could operate with a $75\text{ }^{\circ}\text{C}$ source temperature using silica gel as adsorbent; however, it could operates with other adsorbents, but requiring more source of temperature.

Liu *et al* (2005) have developed a prototype (Fig. 7) that has two adsorbers, two condensers and two evaporators, which are arranged in two vacuum cameras. This prototype did not need valves.

Each adsorber, containing 26.4 kg of silica gel, consists of nine sets formed by perforated plates forming a rectangular prism where the silica gel has been placed protected by a wire gauge No 50.

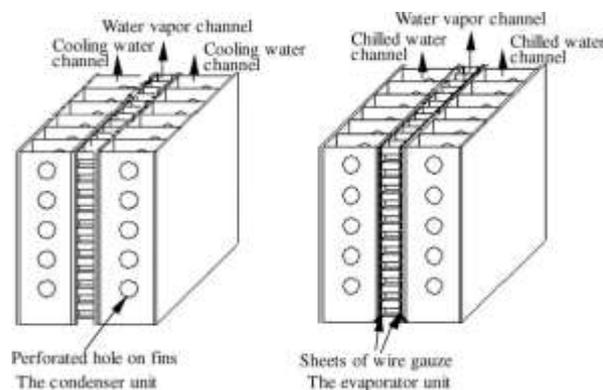


Fig. 7 Condenser and evaporator (Liu *et al*, 2005)

For this prototype, with the heat source of temperature of $85\text{ }^{\circ}\text{C}$ and a cooling water inlet temperature of $25\text{ }^{\circ}\text{C}$, it gotten a chilled water of $14\text{ }^{\circ}\text{C}$ and a COP of 0.365.

The table II present a comparative form the results of tests to these prototypes of adsorption refrigeration that use the pair silica gel - water.

TABLE II SUMMARIZED SURVEYED ADSORPTION REFRIGERATION SYSTEMS USING SILICA GEL - WATER PAIR.

Ref.	T _H (°C)	SCP W/kg	COP	T _M (°C)	T _L (°C)	Cooling power (kW)	Cycle time (min)	Nº. of bed
[5], [15]	86.8	102.1	0.4		16.3 - 21.1	10.62	32	N/A
[16]	87	208	0.62	25	12	3.6	15	2
[17]	60 – 90	0.5 – 85	0.55	30	15	N/A		N/A
[18]	80 – 95		0.3 – 0.6	35	10			
[19]	75 – 95		0.5		10 - 15	3.5	15 - 30	2
[20]	70 – 85		0.36	25	14	2 – 7.3		

Source: Adapted of Hamdy *et al.* (2015)

3.2 Matrix of contradictions - TRIZ

According the analyzed prototypes, the aimed is to get an acceptable COP with not very high source of temperature. As the lower driving temperature required is a function of the characteristics of the material adsorbent, then when the driving temperature decrease the refrigeration effect also decreases.

So the technical contradiction could be expressed as: When the driving temperature improves decreasing, then the refrigeration effect gets worse.

TABLE III MATRIX OF CONTRADICTIONS TRIZ

	Technical parameter that get worse: 21 - Power
Technical parameter that improve: 17 – Temperature	Inventive principles suggested: 2, 14, 17, 25

According of the matrix of contradictions TRIZ, the inventive principles suggested are:

- 2 - Taking out
- 14 - Spheroidality
- 17 - Another dimension
- 25 - Self-service

In addition, the cycle time depends mainly on heat exchanger type, its efficiency, the ratio metal/adsorbent mass, thickness of adsorbent, etc. Therefore, the cycle of Grisel *et al* (2010) is the faster due to the heat exchanger type (flat tube and fins).

3.3 Results

According to the results of the tests on prototypes of adsorption refrigeration systems found in the literature, the following parameters are considered for the conceptual design of the system to be proposal:

- A small capacity chiller with nominal cooling powers around in the range of 3.5 kW - 4.5 kW.
- A cooling temperature between 10 and 15 °C
- 85 °C is the temperature considered to operate the machine.

According to the inventive principles TRIZ suggested: the adsorber that contain the silica gel will be spheroidal and could be put in an exchange with another refrigerant for get a cascade effect.

In concordance with Alvarez & Barrantes (2016) considering a chamber for the transport of food with a relative moisture 90% and for a storage temperature 10 °C and environmental temperature of 25 °C for fruits, and slow air velocity 0.5 m /s, the thermal charge will be determined.

For the charge determination, it is considered 1.12 ton of fruits with an arrangement in 56 box with standard dimensions (CF1 0.6 m x 0.4 m x 0.3 m) with a capacity of 20 kg/box.

Applying the ASHRAE (2014) methodology, it was obtained a thermal charge of 4 kW that will be the chilling cooling power, which it is in the range of 3.5 kW - 4.5 kW.

4. CONCLUSIONS

After the comparative analyze of different prototypes of adsorption refrigeration it was found a quasi-convergence of them, with some variants as the impregnation with ClCa in one case or the use of heat pipes in another.

In function of this data it was chosen the characteristics and size for a new conceptual design.

With the aim of the matrix of contradictions of the inventive methodology TRIZ, it was introduced some specific characteristics for this new conceptual design.

The thermal charge adopted was for the transport of fruits at 10 °C.

Therefore, with this proposal is possible to get a fast positioning in the adsorption refrigeration topic, which usually could require more than 20 years as said Wang (2008).

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