SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications

CETIAT
Together, Innovate and Assess

CO2 HEAT PUMPS

COMPONENTS AND SYSTEMS

SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications

CETIAT
Together, Innovate and Assess

CO_2 HEAT PUMPS

- *Tests performed at CETIAT & CETHIL*
- *A marketed application for water heating*
- *Tear-down of an EcoCute unit*
- *Other applications (water heating)*
- *Component technology and issues*
- *Conclusions and perspectives*

CO_2 HEAT PUMPING APPLICATIONS

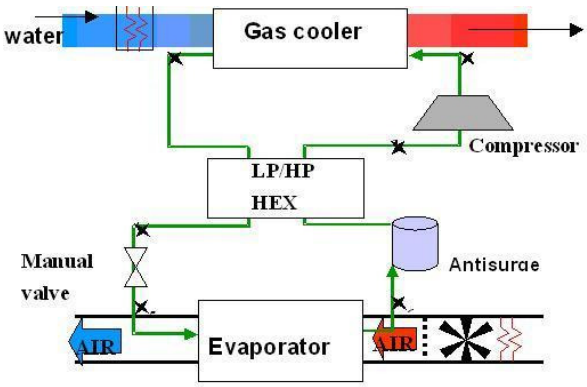
- *Transcritical cycle leads to :*
  - *high temperatures (120 °C)*
  - *large temperature glides (from 120 °C down to heat rejection media temperature - typically 40 °C)*
- *Cycle favours:*
  - *large temperatures changes for heat rejection media*
  - *simultaneous ("integrated") production of cold and heat*
- *"niche" application : hot water production (large ΔT)*

SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

CETIAT/CETHIL TEST RIG

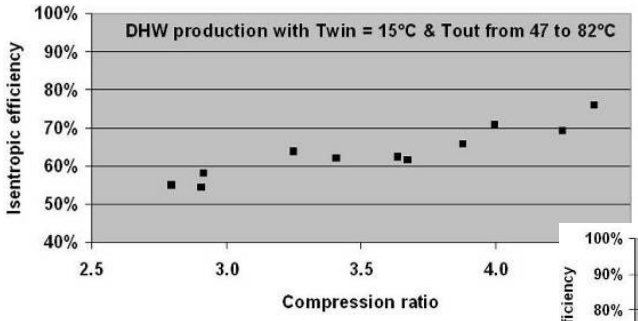
- *Test rig :*
  - *Bock compressor - w/ variable speed drive (110 cc, 500-2500 RPM)*
  - *Air-to-CO2 evaporator (finned coil)*
  - *Gas cooler : collaboration with CIAT*
    - *316L tube-in-tube hex - about 6 m long*
    - *CO2 flowing in four 6 mm tubes*
    - *water flowing through annulus*
    - *designed for 12 kW duty, with "classical correlations"*
  - *rig previously working with a smaller compressor : suction line was found to be undersized*

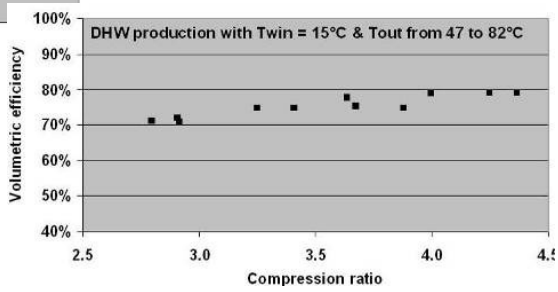
CETIAT/CETHIL TEST RIG



Drehzahlbereich Speed range Vitesse	Verdichtungsenddruck Discharge pressure Pression de refoulement	Verdichtungsendtemp. Discharge end temperature Température de refoulement	Öl Oil Huile
500 - 2500 1/min	< 140 bar	< 140 °C	Fuchs Reniso C85E, C130E, C170E*

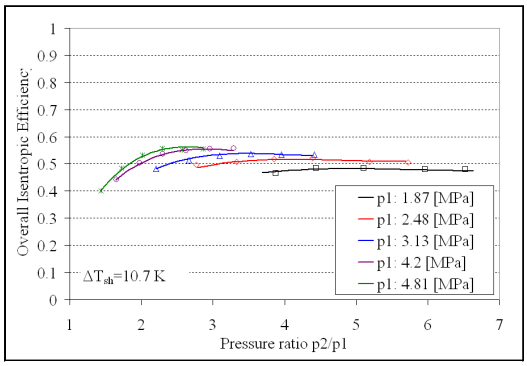
TEST RESULTS



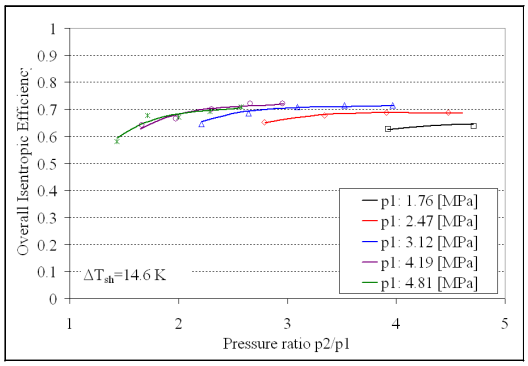


COMPRESSOR PERFORMANCE (Purdue testing)

- *Isentropic efficiency*
  - ***piston***



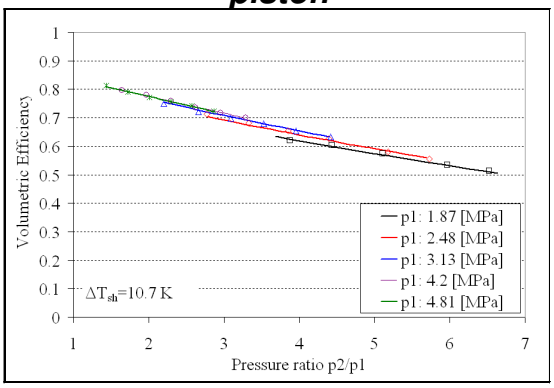
  - ***rotary***



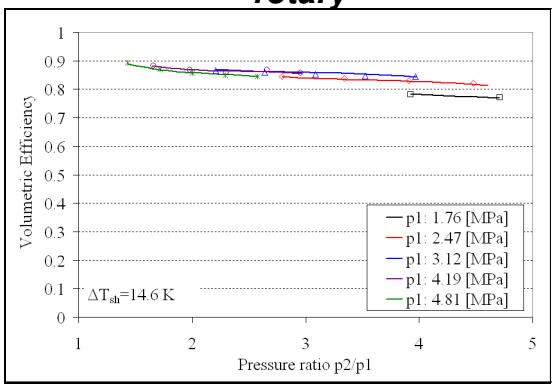
SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

COMPRESSOR PERFORMANCE (Purdue testing)

- *Volumetric efficiency*
  - ***piston***

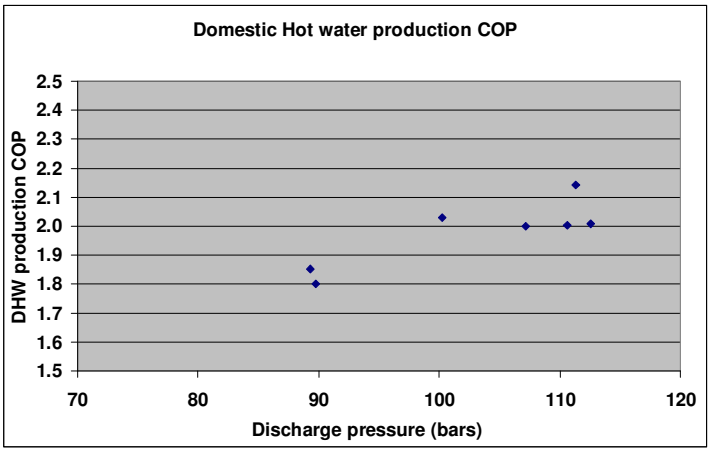


  - ***rotary***



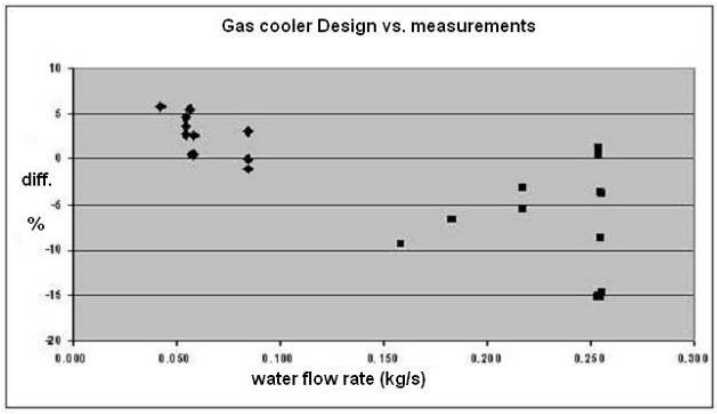
TEST RESULTS

suction line not appropriate for duty, which lowered COP



Gas cooler design : duty comparison

- *Gas cooler designed with stepwise method and classical correlations*
- *water side dominant and correlation not fully known ?*

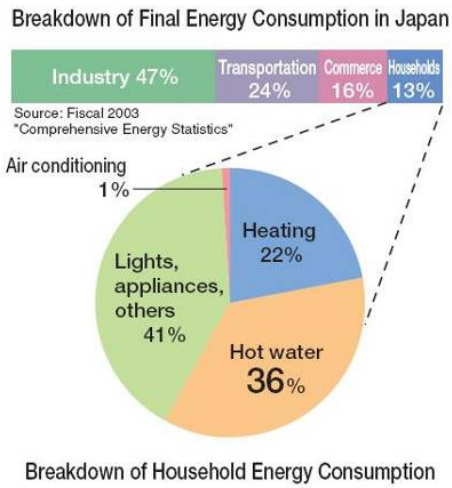


OPERATING PROBLEMS

- *Compressor seals failed twice during testing*
  - *compressor speed too low ? The initial testing rpm was below the recommended speed (500-2500 rpm)*
  - *second failure occurred later (700-800 rpm)*

APPLICATION : JAPANESE MARKET

- *Particularities :*
  - *High electricity prices*
  - *Price differential depends on usage period*
  - *Hot water :*
    - *36% of households consumption vs. 10% in France*
    - *nearly 5% of final energy consumption in Japan*



JAPANESE MARKET

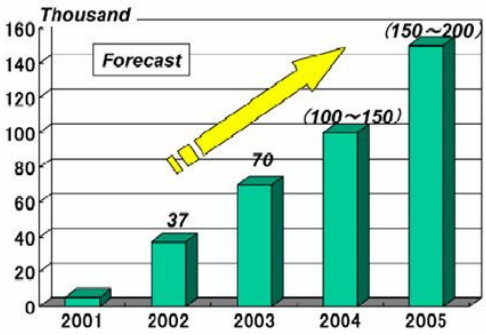
- *Joint development of HPWH by Japanese companies & Shecco*
  - *Hot water cost : 3 - x times less than electrical heating (usage during off-peak tariffs)*
  - *Heat pump subsidised by government (approximate price 5000 euros) - overall ~20% reduction*
  - *"Ecocute" manufactured and sold by 17 companies (Mitsubishi, Daikin, Sanyo, etc.)*

SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

ECOCUTE HEAT PUMP

- *Domestic hot water production (unit tested @ Cetiat)*
- *marketing started in feb 2002, only in Japan*
- *nominal heating capacity : 4.5 kW*
- *CO_2 charge : 1.38 kg*
- *2 separate units :*
  - *Hot water production unit (outdoor unit)*
  - *Hot water storage vessel (300 l capacity)*
  - *tap water : up to 60 °C*
  - *bath water : up to 80 °C*
- *Sanyo Model recipient of "Innovation award" in Interclima 2006 expo. (Paris)*

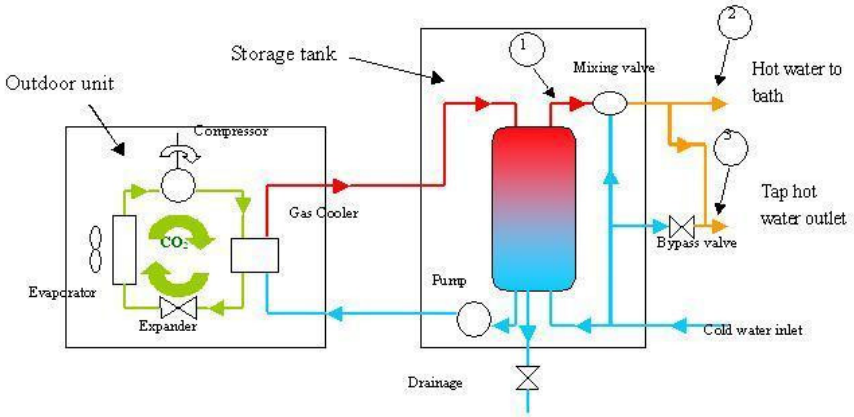
THE ECOCUTE CO_2 HEAT PUMP



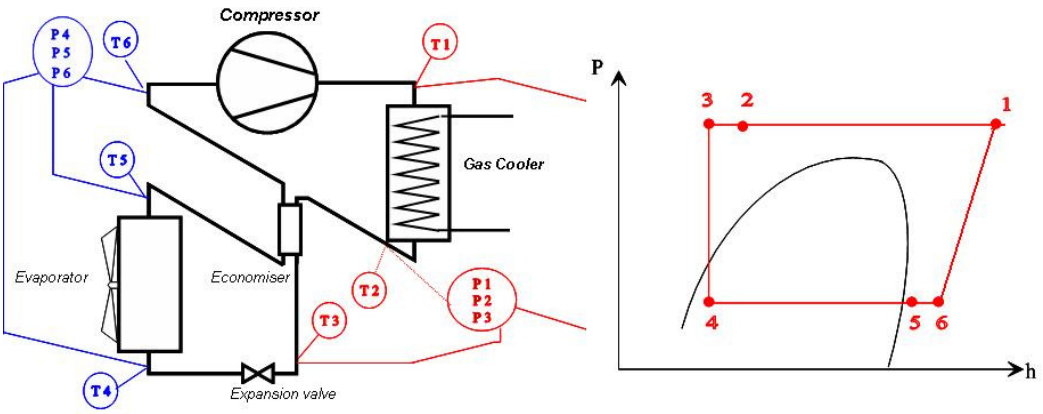
Yr 2005 sales > 225 000 units

TARGET : 5.2 million units in use by 2010

ECOCUTE ARCHITECTURE



ECOCUTE TESTING AT CETIAT



ECOCUTE TESTING

- *Instrumentation :*
  - *pressure sensors (up to 200 bars)*
  - *compressor frequency*
  - *operating variables measured (T,P, water flow rate)*
- *Safety measures*
  - *shut-down at pressures above 150 bars*
  - *safety valve installed at suction (100 bars)*
  - *portable oxygen detector in testing room*

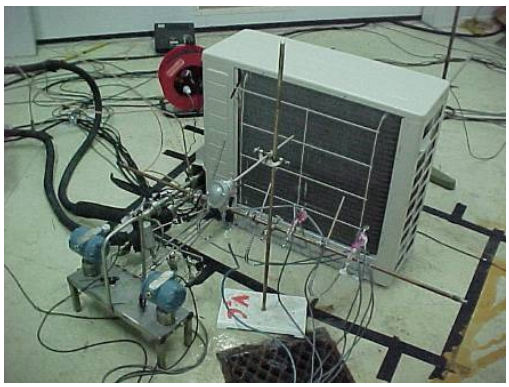
ECOCUTE TESTING

- *Others :*
  - *instrumentation required unit discharging and charging*
  - *Observations : CO2 very soluble in oil*
- *COP less than indicated by manufacturer*
  - *ex : COP = 1.9 vs 2.5 claimed (23% diff.)*

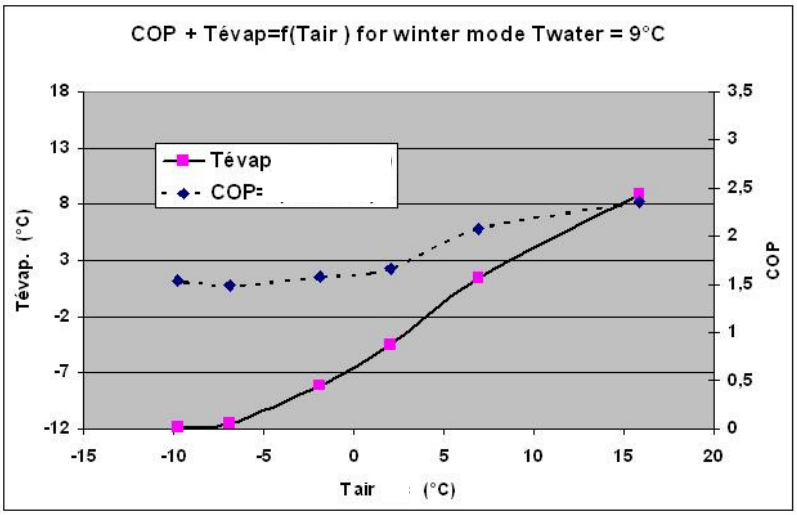
SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

ECOCUTE TESTING

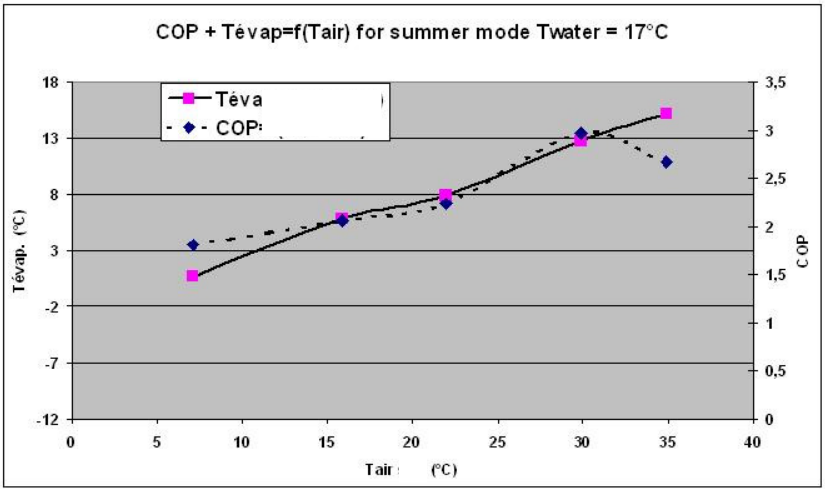
ECOCUTE TESTING



ECOCUTE TEST RESULTS



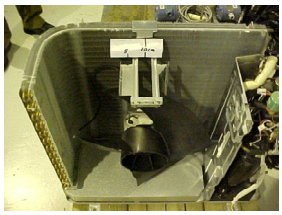
ECOCUTE TEST RESULTS



ECOCUTE TESTING

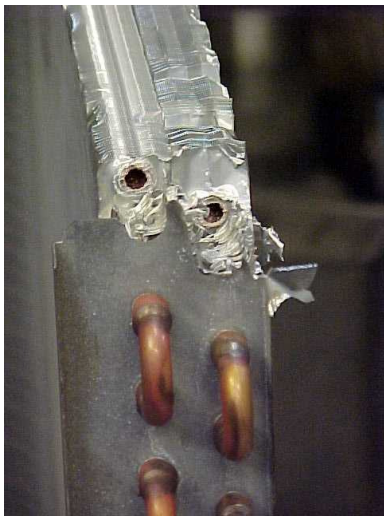
- *Reasons for COP discrepancies :*
  - *were the testing conditions the same ?*
  - *Tolerances in Japan results in COP of +/- 15%*

ECOCUTE OUTDOOR UNIT TEARDOWN

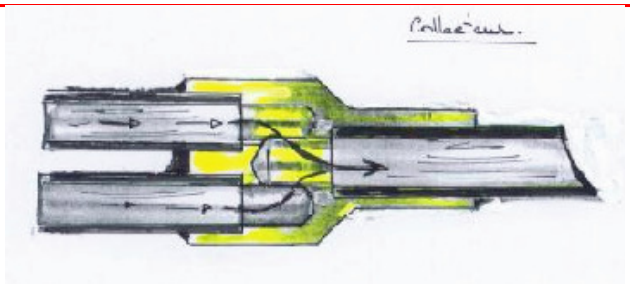


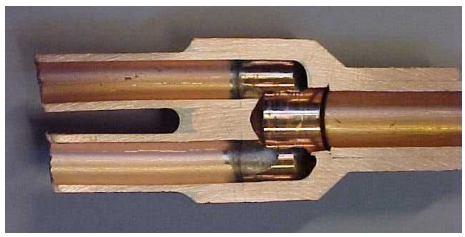
SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

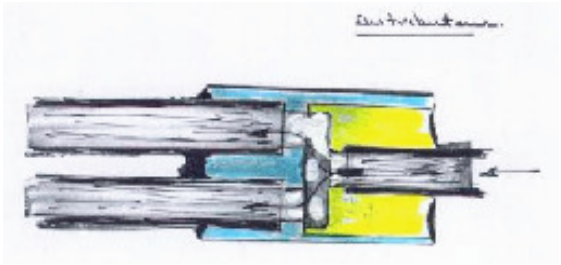
ECOCUTE OUTDOOR UNIT TEARDOWN

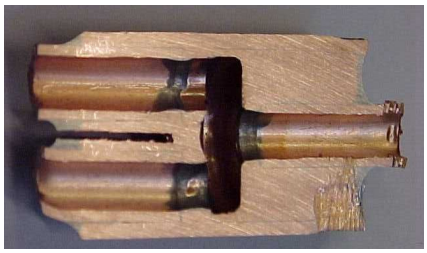


ECOCUTE OUTDOOR UNIT TEARDOWN





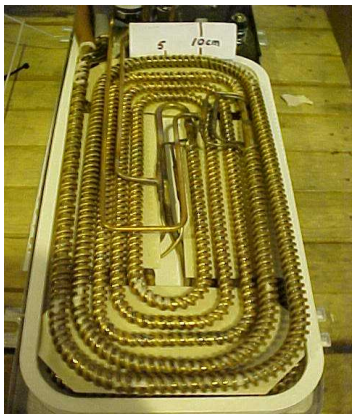




UNIT TEARDOWN

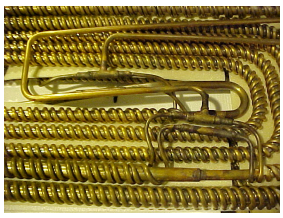
Separation of oil and CO2 :gravity, coalescence and centrifugal action

GAS COOLER



SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

GAS COOLER



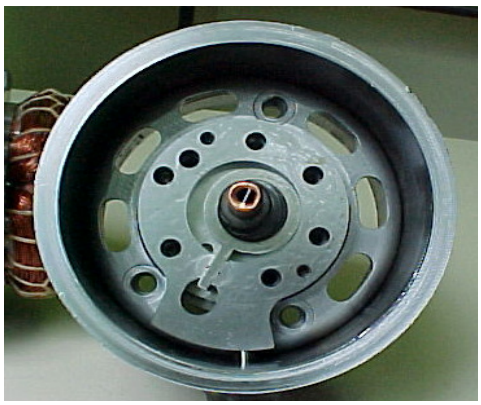
Rugged and simple design
(overall U ~ 250 W/K/m²)

HIGH PRESSURE CONTROL

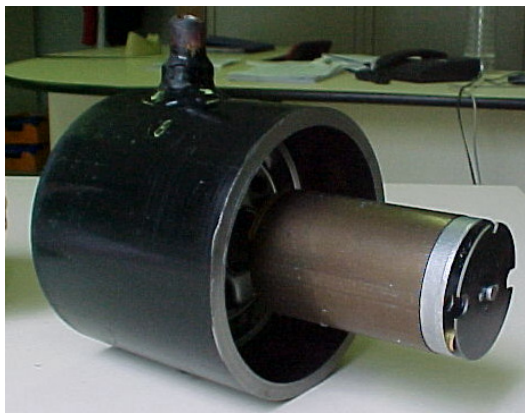
- *Extra-tank (large diameter pipe) provides for charge control on high pressure side*

LP-HP HEAT EXCHANGER

COMPRESSOR (SWING TYPE)

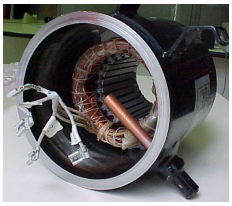


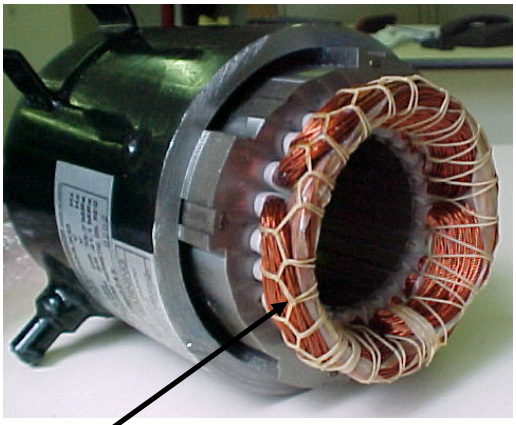
High pressure (discharge) on shell side



Permanent magnet rotor

COMPRESSOR MOTOR (PM-BLDC)





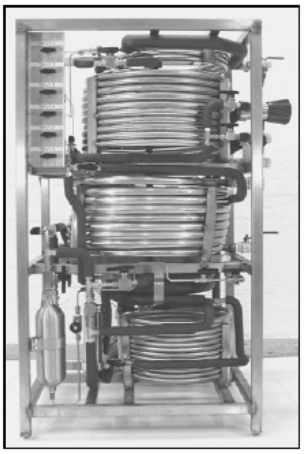
Note the stator windings (« chignon)

HEAT PUMPS : OTHER DEVELOPMENTS

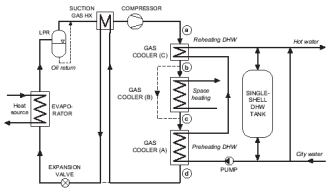
- *UTC (Carrier) 20-60 kW unit : under field test*

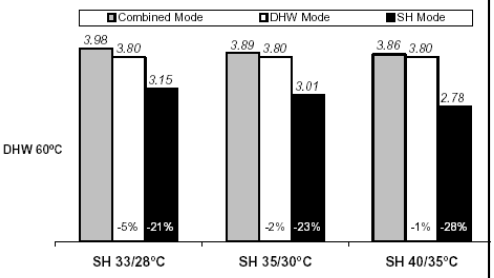
CO_2 HEAT PUMPS : OTHER DEVELOPMENTS

- *Northern Europe : combined WH/Heating*



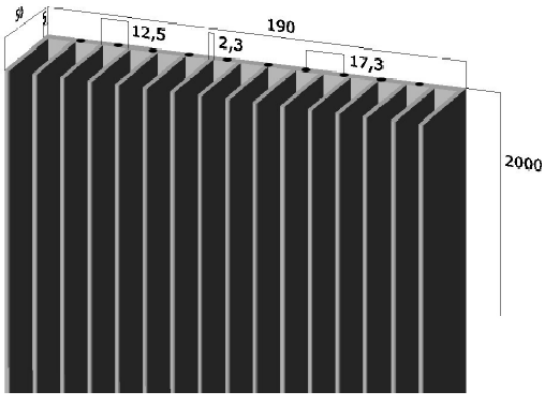
OTHER APPLICATIONS





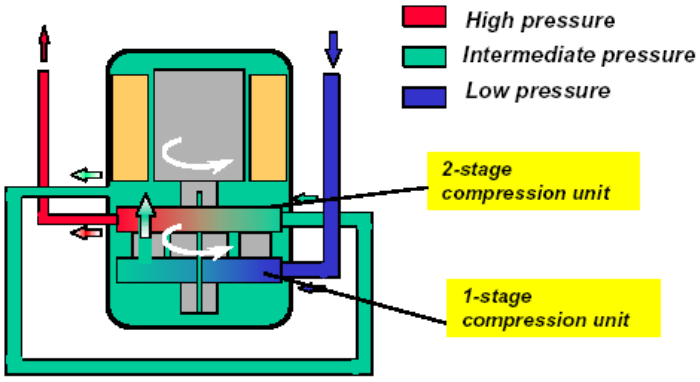
"FANLESS RADIATOR"

- *direct use of CO2 in domestic radiators (P.Neksa,Glasgow 04)*
- *counter-current flows of air and CO2*



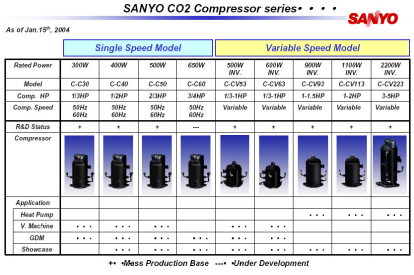
COMPONENT TECHNOLOGY AND ISSUES

- *Compressors : japanese manufacturers (e.g. Sanyo)*



Example application

Compressors


SANYO CO2 Compressor series

As of Jan.15th, 2004

	Single Speed Model				Variable Speed Model				
Rated Power	300W	400W	500W	650W	500W INV.	600W INV.	900W INV.	1100W INV.	2200W INV.
Model	C-C30	C-C40	C-C50	C-C60	C-CV53	C-CV63	C-CV93	C-CV113	C-CV223
Comp. HP	1/3HP	1/2HP	2/3HP	3/4HP	1/3-1HP	1/3-1HP	1-1.5HP	1-2HP	3-5HP
Comp. Speed	50Hz 60Hz	50Hz 60Hz	50Hz 60Hz	50Hz 60Hz	Variable	Variable	Variable	Variable	Variable
R&D Status	+	+	+	---	+	+	+	+	+
Compressor									
Application									
Heat Pump								• • •	• • •	• • •
V. Machine	• • •	• • •	• • •		• • •	• • •			
GDM	• • •	• • •	• • •	• • •	• • •	• • •			
Showcase		• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •

+ •Mass Production Base --- •Under Development

Compressors : others

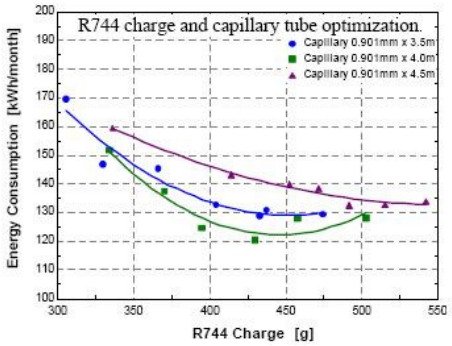
- *Bock (Germany)*
  - *a "pre-series" and a small fleet of buses working with CO2 based A/C - up to 20 kW heating*
- *Danfoss : small capacity "ready for production"*
- *Dorin (Italy) - 3 to 25 (?) kW : thorough testing by Carrier during heat pump field tests – problems claimed to be solved.*
- *Tecumseh : under development*
- *Others :*
  - *Japanese manufacturers (most have proprietary designs in Ecocute products)*
  - *Embraco (Brazil)*
  - *ACC (Spain)*

HP control with capillary tube (Embraco, Brazil)

- *1.75 cc/860 W cooling @-10°C evap/83 bar discharge*
- *About 25% savings claimed vs. R134a system*

GDM tested.

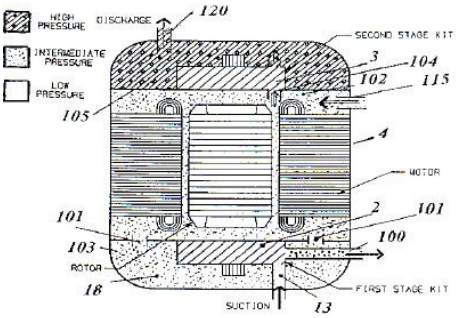
CO_2 compressor

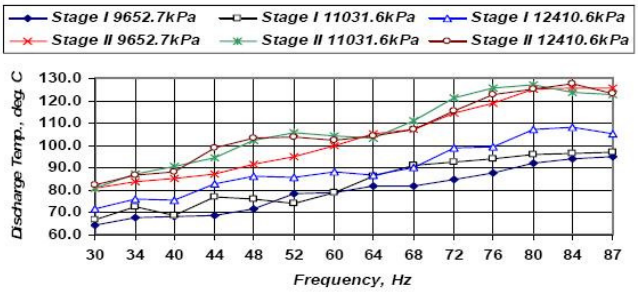


- *Applicable to small air-to-air recovery heat pumps ?*

Tecumseh

- *Oil separator divided OCR by a factor of 5*
- *2-stage rotary hermetic (16 and 11.7 cc/ 12 kW Cap)*

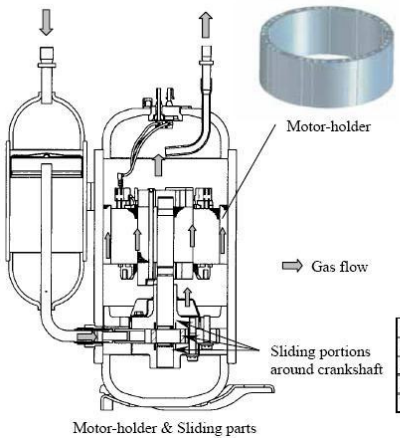




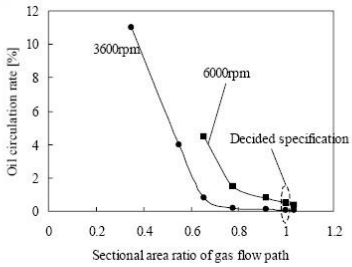
Effect of the compressor operational speed on the Stage I & Stage II Discharge Temperatures at Discharge Pressures 9652.7kPa, 11031.6kPa, and 12410.6kPa.

Mitsubishi rotary compressor

- *Design lowers gas velocity and hence oil carry-over*
- *OCR claimed to be < 0.1%*



Motor-holder & Sliding parts



Specification of the CO2-Single Rotary Compressor

Compressor type	Single Rotary
Displacement	4.5cm^3
Refrigerant	R744 (CO2)
Motor	BLDCM (Joint-Lapped Motor)
Usage	HP Water-Heater 4.5kW/6kW

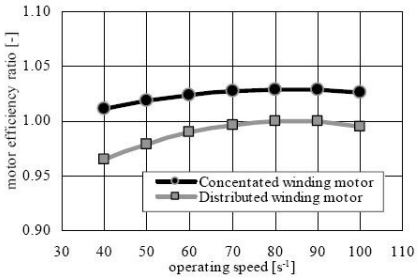
Daikin : improvement of swing compressor

- *Improved «chignon » - less stator electrical losses*
- *Improved fixation to improve acoustics*

Distributed winding motor (original)

Concentrated winding motor (improved)

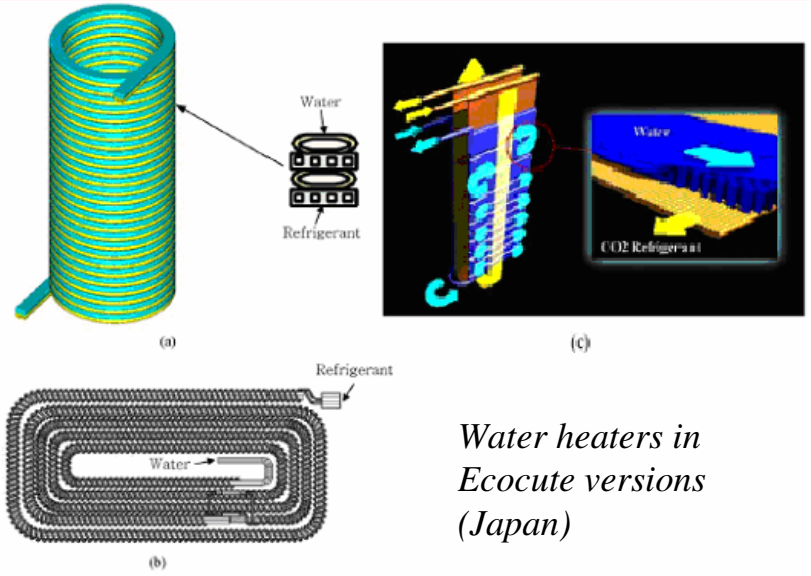
	Original compressor	Improved compressor
Compressor type	Swing	Swing
Motor type	Distributed winding motor	Concentrated winding motor
Displacement	3.7cc	4.2cc
Discharge port height	5.0mm	2.5mm
Motor stator fixation method	One section welding	Two sections welding



HEAT EXCHANGERS

- *Challenges :*
  - *high operating pressures*
  - *domestic hot water : separate channels for the heating medium (CO2) and water (double wall)*
  - *classical design methods are not very accurate (for gas cooler) because no reliable correlation exists in the open literature....large change in thermophysical properties from supercritical gas to liquid*
  - *"overall" LMTD design method fails because of internal temperature pinch in gas cooler (T-H curve)*

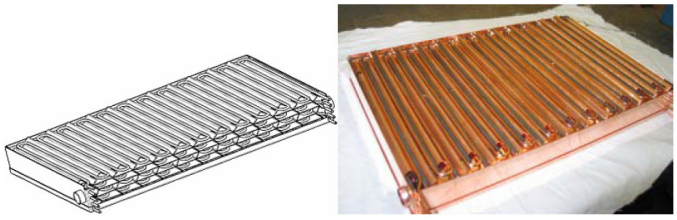
HEAT EXCHANGERS : TECHNOLOGIES



Water heaters in Ecocute versions (Japan)

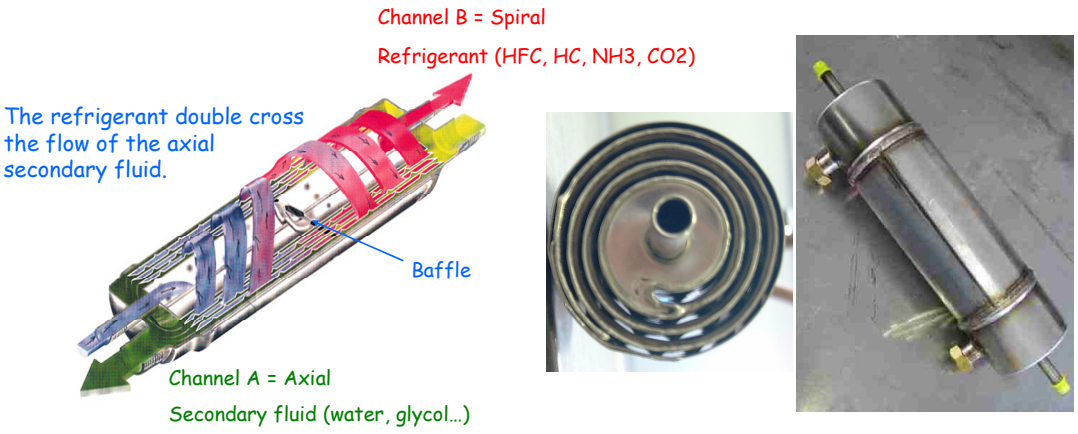
Water-to-CO2 heat exchangers

- *Stiebel-Eltron*



Water-to-CO2 heat exchangers

- *Spiral heat exhangers : Spriec (France)*

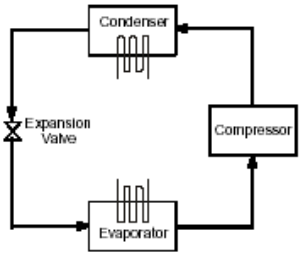


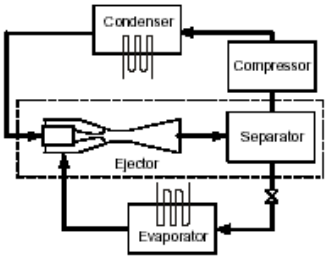
PERFORMANCE IMPROVEMENT

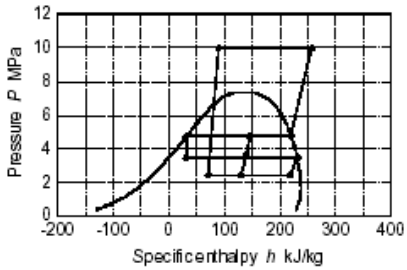
- *Poor compressor performance (piston-type)*
- *Need :*
  - *to take "full" advantage of the large temperature change in the gas cooler*
  - *different cycle architectures (in terms of controls, but also for thermodynamic optimisation) ?*
  - *expansion work recovery ?*

PERFORMANCE IMPROVEMENT: EJECTOR ?

- *Claimed improvement : 20% in Denso Ecocute*

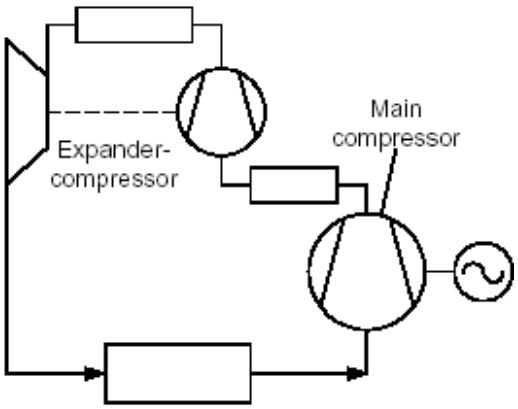






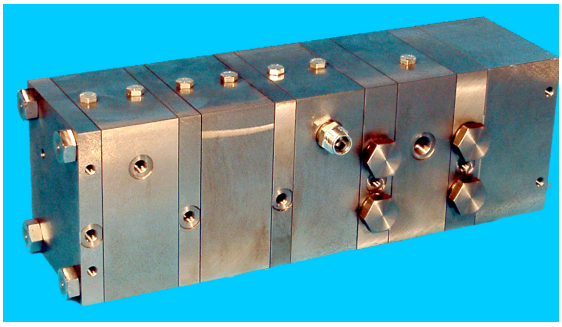
PERFORMANCE IMPROVEMENT : EXPANDER

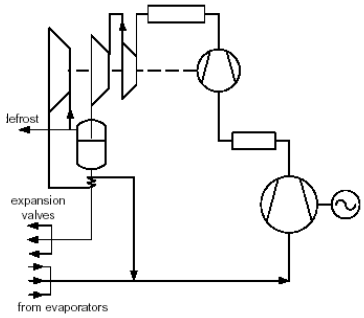
- *Expansion energy used to drive extra - compressor*



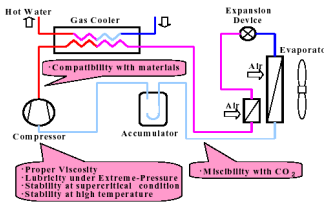
PERFORMANCE IMPROVEMENT : EXPANDER

- *Expander and extra compressor : linear type*
- *System was inspired from water pumps (steam)*
- *"compact" 3-stage system proposed*





LUBRICANTS ISSUES



LUBRICANTS

- *CO_2 high density (5 x ρ R22) and CO2 solubility in oils poses problems – **CO_2 IS A SOLVENT***
- *Separation efficiency requires lower vapor velocity*
- *Lab Tests : with rotary compressors, oil separator is necessary because carry-over is too important*
- *Compressor design changes to decrease oil carry-over ?*
- *Comparison PAG, POE, PVE and Polycarbonate :*
  - *PAG is best suited for CO_2 ?*

SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

CONCLUSIONS

- *Limited range of available components : kick-off for compressors, but HP Gas Coolers offer is limited – and expensive (scale effects)*
- *Current developments aim at targeting the residential heating application (especially the revamping market in Europe)*
- *limited performance : need for architecture improvement ? ejector, use of expansion energy ?*

Outlook for further HP applications ?

- *Combined production of heating/cooling*
- *Domestic tumble-dryers*
- *Humidity control (air cooling and dehumudifation thru evaporator and heating thru gas cooler)*
- *Multi-functional domestic heat pump with use of cooling*
- *Heat recovery in ventilation system*
- *…*

SHERHPA
Sustainable Heat and Energy Research for Heat Pump Applications
CETIAT
Together, Innovate and Assess

***Installation of a* CO2/CO2 cascade supermarket system in Denmark :**

"Components for transcritical systems are few and far between, and those that are commercially available are very expensive. However, new legislation keeps pushing for lasting solutions and we wanted to get started and gain experience when the opportunity arose"

Torben Olsen (Danfoss Internet site)