DTU Library

Direct drive solar coolers

Pedersen, P. H.; Katic, I.; Jensen, J. K.; Markussen, W. B.; Moeller, H.; Cording, C.

Published in:
Proceedings of the 25th IIR International Congress of Refrigeration

Link to article, DOI:
10.18462/iir.icr.2019.1024

Publication date:
2019

Document Version
Peer reviewed version

Manuscript ID: 1024
DOI: 10.18462/iir.icr.2019.1024

DIRECT DRIVE SOLAR COOLERS

Per Henrik Pedersen[(a)], Ivan Katic[(a)], Jonas Kjær Jensen[(b)], Wiebke Brix Markussen[(b)], Hendrik Moeller[(c)], Claus Cording[(d)]

[(a)]Danish Technological Institute
Gregersensvej 2, DK-2630 Taastrup, Denmark,
prp@teknologisk.dk
[(b)]Technical University of Denmark, Department of Mechanical Engineering
Nils Koppels Allé, Building 403,
2800 Kgs. Lyngby, jkjje@mek.dtu.dk
[(c)]Nidec Global Appliance Germany GmbH
Mads-Clausen-Str. 7, 24939 Flensburg, Germany
hendrik.moeller@mail.nidec.com
[(d)]Vestfrost Solutions
Falkevej 12, DK-6705 Esbjerg Ø,
CLC@vestfrostsolutions.com

ABSTRACT

For many years, photovoltaic power has been used in areas without grid electricity for vaccine refrigerators with a lead-acid battery to store electric energy and to provide the start current for the compressor. The problem with this technology is that the lifetime of the battery is short due to deep discharging of the battery during periods with low irradiance and high ambient temperature.
The development of solar "direct drive" refrigerators started in 1999 at Danish Technological Institute (DTI).
It was demonstrated that the energy density of ice produced by a compressor is at the same magnitude as the lead-acid battery. As of to date (January 2019), 40 direct drive vaccine coolers from eight different manufacturers are listed on the website of the World Health Organization (WHO), with the technology being one of the fastest growing technologies in the vaccine cold chain.
This paper describes the status and new development and discusses how the technology can be used for other purposes in the future. The paper also discuss how remote monitoring can help to prevent destruction of vaccines by early warning and automatic call for service.

Keywords: Photovoltaic, Direct drive, Vaccine coolers, Natural refrigerant, Isobutane, Remote monitoring.

1. INTRODUCTION

Health organizations have developed a cold chain system with health centres in regions without grid electricity, and correct storage of vaccines has been a challenge for them. Many vaccines must be kept at temperatures between +2 ˚C and +8 ˚C. Some deviations in the upper end can be allowed but freezing would immediately destroy the vaccines resulting in the loss of potency.
The vaccines used in immunization programmes are stored in a dedicated special vaccine cooler approved and prequalified by the World Health Organization (WHO) and listed in the "Performance, Quality and Safety" (PQS). New and traditional vaccines used in country immunization programmes are expensive and often much more expensive than the refrigerators themselves in the long run.
Since the early 1980s, photovoltaic power has been used for such refrigerators with a lead-acid battery to store power and provide start and operating current to the compressor. The problems

with this solution are the relatively high cost and the limited lifetime of the battery due to high ambient temperatures and deep discharging of the battery during periods with little sun as well as the lack of timely planning for the replacement of the batteries.
Therefore (and because of lower investment costs), gas and kerosene powered absorption refrigerators have been standard in the remote setting health facilities until recently. Absorption refrigerators need a constant fuel supply, and they are, therefore, expensive to run over its lifetime. Moreover, the temperature control is often poor, which results in expensive vaccines being destroyed.
The above challenges formed the background for developing and testing solar “direct drive” (DD) refrigerators, where the energy is stored in ice instead of a battery and thereby eliminating the practical and financial difficulties with battery replacement.
The development of solar “direct drive” refrigeration started in 1999 at Danish Technological Institute (DTI). Here, a prototype was produced with funding from the Danish Energy Agency. A normal DC compressor (with high start current) was used and a big capacitor helped to start the compressor. It was demonstrated that the energy content in ice produced by this compressor was higher than the energy content in a lead-acid battery, in terms of both volume and weight. (Pedersen and Katic, 2016).
Contact was established to international organizations, and after a meeting in Frankfurt the “SolarChill Partnership” was established with United Nations International Children's Emergency Fund (UNICEF), WHO, United Nation Environmental Program (UNEP), Deutcshe gesellschaft für Internationale Zusammenarbeit (GIZ), Program for Appropriate Technology in Health (PATH), Greenpeace International and the Danish Technological Institute (DTI) as partners. The goal was to develop and implement PV-powered vaccine refrigerators without batteries but using natural refrigerants. (Pedersen and Maté, 2007).
At the same time, a compressor manufacturer developed a DC-compressor for R600a and with “soft start”, which made it possible to wire the compressor directly to the PV-panels (DD – direct drive). In 2004, with additional field tests carried out in three countries (Indonesia, Senegal and Cuba), the results were so promising that the partners chose to continue the further development of the solar direct drive refrigerator to pre-qualify the product for WHO PQS standards for safe storage of vaccines. (Pedersen and Maté, 2010).

2. CURRENT STATUS

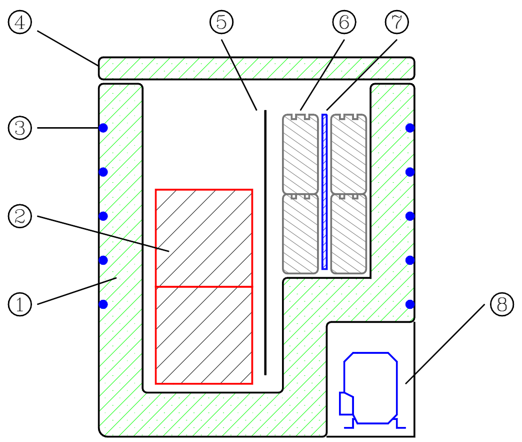
This section describes the current status for vaccine coolers for health stations in rural areas in developing countries.

2.1. Ice storage versus batteries

Relief organizations want to avoid lead batteries as the main source of energy to keep the vaccines cold during night-time and periods with little solar power. Previous experience has shown that additional costs are related to the batteries in that high ambient temperatures and frequent deep discharging result in a fast degradation and short life cycle of the batteries. This by itself is one key reason why the solar battery powered refrigerators have often been more expensive than kerosene or LPG-powered absorption refrigerators.
In the SolarChill project, ice bank “batteries” have been developed as an alternative source of energy storage. In (Pedersen and Katic, 2016) there is an analysis and comparison between the energy storage in a typical lead battery and in ice.
The conclusion is that the cooling energy capacity of ice storage is in the same order of magnitude as that of a traditional lead battery on volumetric and mass basis. The cooling energy capacity of ice storage is approx. 123 % higher (for the ice storage) on weight basis and approx. 21 % higher on volume basis.
Commercialization of long-life lithium based batteries with high energy density might change the role of battery storage in solar refrigeration. However, the ice storage in SolarChill is the simplest and most cost-efficient solution so far. A disadvantage when using ice storage is that the ice has to be stored inside the insulation of the cabinet. Thus, the net volume inside the refrigerator will be smaller.

2.2. Compressor for "Direct-Drive" (DD)

There are only very few PV direct drive compressors available on the market today. The most common model is the BD-35K. The compressor manufacturer also developed a new integrated electronic control for the compressor, which ensures that the photovoltaic panels can be connected directly to the compressor without external control. The electronic control also ensures a "soft start", which is important when no battery is used.
The electronic control is equipped with an adaptive speed control (Adaptive Energy Optimizer – AEO). By using this control, the compressor will stepwise speed up from low speed to maximum speed in steps of approx. 12.5 RPM/min. If the photovoltaic panels cannot provide enough power, the compressor will stop and after a short while it will try to start again. The compressor will try to start every minute, and once the power from the panels is enough, the compressor will start at a lower speed. The first start in the morning is at approx. 2500 RPM. After a thermostat cut-out, the compressor will start up at the latest speed minus 400 RPM. The speed range is from 2000 to 3500 RPM.
The controller accepts a voltage between 10 and 45 V. The voltage from photovoltaic panels can vary, and a wide voltage range is an important and crucial feature for solar powered refrigerators and freezers. When using 12 V modules, the starting current of the compressor is less than 3 A; typically, there will be enough power a few hours after sunrise. The compressor runs continuously at about 3 A at lower speed. Using a standard compressor control, the start current would be much higher, which requires much bigger PV-panels or the use of a big capacitor to help start the compressor.
In the prototypes (chest and upright), the expansion device is a capillary tube with a heat exchange to the suction line. In the chest type cabinets, integrated skin condensers are used as in most chest freezers.
The evaporator in the vaccine chest refrigerator is a wire-on-tube-type placed in the ice storage as shown in figure 1a. The evaporator in the upright-type is a box-type roll bond-aluminium evaporator as known from old refrigerators with a small freezer compartment.



1 – Cabinet
2 – Vaccine compartment
3 – Skin condenser
4 – Lid
5 – Internal wall, insulated
6 – Ice storage (26 „ice packs", 600 ml)
7 – Evaporator, wire on tube
8 – Compressor.

Figure 1a: Figure with basic principles for the first prototype vaccine cooler.

Figure 1b: Photo of a DD solar compressor. The integrated solar electronic control is placed on the left-hand side of the compressor.

2.3. Field test experience and commercialization

DTI has been running an extensive field test program, where the performance of the first series of solar DD appliances was documented in terms of practical use in health clinics.
Pedersen and Maté (2007) explain how the field test of this vaccine cooler took place in Indonesia, Senegal and Cuba using 180 W photovoltaic panels (3*60 W peak). Moreover, the tests show the hold-over time of about five days without any energy available. The field test lasted about one year and the ice banks were never completely melted, except when the connections to the PV-panels were disconnected intentionally. However, the vaccine temperature was not always within the preferable range of 2-8 °C in connection with this early prototype.
Vaccine specialists have developed new criteria for DD vaccine coolers. This work was done in cooperation with the partners of the SolarChill partnership and other technical experts.
The first generation of the WHO PQS (Performance Quality Safety) criteria for DD vaccine refrigerators was introduced in 2010, and the first test for WHO approval was conducted at DTI in 2010.
The WHO PQS prequalification is a condition in most tenders for the procurement of cold chain equipment for organizations that procure cold chain equipment used for storage of vaccines. This ensures the quality of vaccines stored in these products as safe for use in immunization programmes.
Currently there is a new field test going on with a selection of WHO approved DD vaccine coolers in a GEF (Global Environmental Facility) project.

2.4. Two main types of DD vaccine refrigerators

The WHO website holds an increasing number of approved DD vaccine coolers. In January 2019, it contained 40 units from eight different manufacturers. 37 of the units use the natural refrigerant isobutane (R600a). Three of the units use a HFC-refrigerant (R134a).
Today, there are two main types of DD vaccine coolers on the market.
The first type is the ice-pack type, where the ice storage (and/or PCM-materials) is built into the walls of the cabinet or in a special compartment close to the evaporator. This type of DD vaccine cooler is often based on a chest type cabinet. Such types of cabinets are relatively cheap to manufacture, but precise temperature control may be a challenge.
This (or a very similar) technology is applied in 34 of the 40 DD vaccine coolers on the WHO list in January 2019.

Figure 2: Ice pack type of DD vaccine cooler.

The other main type of vaccine refrigerator is the tank type using a mixture of ice and water surrounding the vaccine chamber. Water has the highest density at about +4 ˚C and with a top-

mounted ice storage. This ensures that water in the bottom of the tank and in thermal contact with the vaccine storage is about +4 ˚C, which is ideal for storage of vaccines, and it eliminates the risk of freezing.
The DD vaccine refrigerators using this technology ensure a very stable temperature and a long hold-over time, but they can be more expensive to manufacture if the special tank is manufactured in smaller quantities.
This technology is applied in six of the 40 DD vaccine coolers on the WHO list in January 2019.

Figure 3: Tank type DD vaccine cooler.

3. FUTURE PERSPECTIVES

The existing refrigeration technology in solar direct drive vaccine coolers is about 17 years old. Therefore, a new R&D project has been started involving the Technical University of Denmark, a compressor manufacturer, a manufacturer of vaccine coolers and Danish Technological Institute, who is the project manager. The Danish Energy Agency is funding the project.

The project started in 2017 and the aim is to develop:
- Concept for a new compressor
- Concept for a new cabinet, new ice storage and remote monitoring.

The compressor will be more energy efficient compared to the present DD compressors. The results from the first prototype, named BDS5.0K tested in lab, primo 2019 shows to fulfil this goal. In addition to this, the variable speed compressor is supposed to have higher cooling capacity and a broader span in capacity. This will give possibilities to use this compressor for bigger cabinets and for new applications in addition to the present use of this type of compressor.
Furthermore, efforts are made to develop a more efficient control strategy (Jensen, Moeller, Katic, Pedersen and Markussen, 2019).
DTI hosted a meeting with the WHO PQS working group in November 2018. In a discussion about future generation of direct drive compressors for vaccine coolers it was the impression that the group wants to avoid dependence on batteries for energy storage – also in the future.
The future cabinet is supposed to have a longer “hold-over time”, which can be met by using bigger ice storage and/or better insulation. The future vaccine coolers are supposed to be remote monitored to ensure safe storage of vaccines and early warning if something goes wrong.
According to the WHO PQS working group, high relative humidity and even presence of water inside the vaccine compartment is a problem. In some coolers creation of mould has taken place. Thus, the next generation of vaccine coolers are supposed to solve this problem.

3.1. Remote monitoring

Refrigerators used for vaccine storage need to be extremely robust and must be able to keep the temperature withing the limits specified by WHO. A spoiled load of vaccine costs thousands of dollars, and manufacturers and users are therefore looking for methods to send early warnings in case of malfunction. In the past, monitoring had to be based on manual readings and download of data, but today IoT technologies are available from many providers of monitoring systems and are already used by some appliance manufacturers. DTI has investigated a range of systems using GSM mobile network for data transmission in connection with a large field test project (SolarChill) for solar direct drive refrigerators.

Ideally, the data acquisition system should have the following characteristics:

- Robust and reliable automatic data acquisition not relying on grid connection or internet
- Easy download of data, preferably automatic transmission
- Not too expensive and simple to install and operate.

In the SolarChill project, the following values are being monitored:

Table 1: List of data monitored by the advanced datalogger and the simple datalogger in the ongoing SolarChill project.

Advanced data logger	Basic data logger
Solar irradiance in plane of array	
Ambient temperature	Ambient temperature
Internal temperatures (4)	Internal temperatures (4)
Relative humidity	
Current	
Voltage	
Open/close events	

Both data loggers are uploading data with a user defined frequency to the manufacturer's server. The user can see and download data from a web portal, and alarms can be sent automatically by email.

Because the project is about solar powered refrigeration in remote areas, there is no grid power nor regular internet connection available at the installation sites. Therefore, mobile network or satellite communication are the only options for daily long distance access to the measurement systems.

For short distance, there are several other wireless technologies available, they may be used for internal communication between sensors and a GSM base station, also called Remote Terminal Unit (RTU) or cellular gateway.

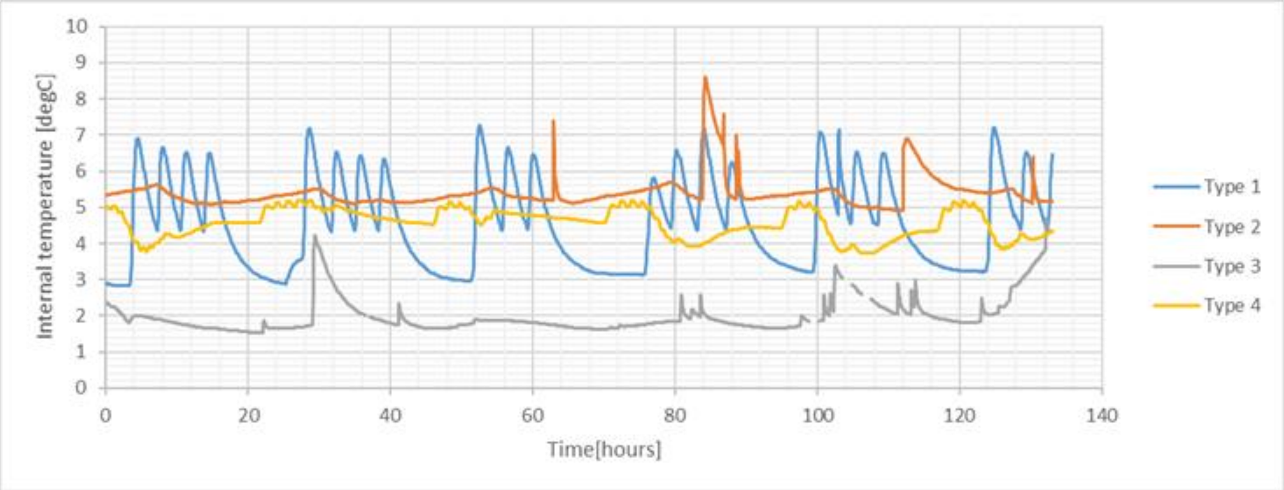


Figure 4: Example of field test data (from four different sites). This figure represents four different models of vaccine coolers in the ongoing SolarChill project. Every type of refrigerator has its own temperature "fingerprint" that may be useful in preventive maintenance.

There are several remote monitoring systems in the market that can be used for temperature monitoring alone. These are either single channel devices (some disposable) or multichannel with replaceable battery power supply. For collection of other data, like solar irradiance and voltage, there are not as many options. These systems are mostly configured with a central GSM gateway or base station that can be connected with or without wire to a range of different sensors. The gateways usually have a considerably higher energy consumption than the integrated sensor systems and needs external power supply for long term operation (Option for PV panel). Some are always connected to the GSM network for near-Realtime monitoring, others are only calling and updating hourly or daily.
Internal power supply of the DAQ system may be provided by either:

- Dry cell batteries (single use)
- Rechargeable batteries (To be occasionally charged from grid or a vehicle)
- PV power from the systems under measurement (Parasitic power)
- Separate PV supply.

The software for cloud based data collection and monitoring is mostly offered as a subscription service per month or per year for each connected device. It could therefore add up to a considerable amount. Most software is proprietary and can only be used with the company's own data loggers.
There is also software paid with a onetime license per user/PC and this could be a cheaper solution in the long term.

3.2. Vaccine coolers - future perspectives

Since the first solar DD refrigerator project in 1999, the cost of PV modules have dropped from about 4 USD/W to 0.4 USD/W or a factor of 10. In the same period, the unit size of a typical panel has increased from less than 100 W to about 300 W nominal power. This means that the same SolarChill refrigerator can now be run with a single PV panel instead of 2-3 panels, translating to simpler mechanical support and circuitry with the invention of plug and play MC connectors. In comparative terms, the retail cost of a single panel of 150 W, which provides enough energy for these products in most tropical climates, would typically be 500 USD, which is about the same cost as a set of high quality batteries. With even cheaper PV modules foreseeable in the future, new refrigerators will not have to focus that much on energy efficiency, but rather on the overall system costs and performance.
The interaction between the PV panel and the compressor can be further improved. Instead of the current "trial and error" method for adjustment of the compressor speed, it would be better if a maximum power point tracker could continuously adjust the compressor speed.

3.3. Other applications - DD coolers for food and drinks

Besides the need for vaccine storage refrigerators, there is a huge need for cooling of food and drinks in regions without a grid. There are only few battery-free coolers available on the market so far, and it is difficult to bring the costs down to a level that is comparable with the conventional household appliances. The power demand for such appliances is much higher than for vaccine refrigerators, and the current DD compressors are not always sufficient. It would be interesting if new and bigger devices could be developed for this market. As an alternative solution, the current models may be used in parallel-configuration.
On an even larger scale, there is a growing interest to use the solar DD technology for commercial cooling demands such as milk cooling, ice production for the fishing industry, cold stores etc. For such applications, it might be better to include a (small) battery bank, so that the PV power can be used for light and other secondary power needs as well.

4. CONCLUSIONS

The SolarChill field test has shown that DD solar cooling is indeed a robust and reliable technology that is particularly suited for cooling in the most remote areas of the world where there are no access to electricity. The uptake of this concept by more and more manufacturers confirms that the idea of directly driven cooling is viable within the medical healthcare market, where reliability is essential. The WHO PQS web-site contains 40 different products of DD vaccine coolers, whereof 36 products are using natural refrigerant (R600a).

For other markets there are still some way to go, mainly because there are only very few DD compressors available, and they are too small for many generic cooling applications.
The future of the DD technology depends on the will of the manufacturer to develop cost-effective and more powerful compressors as well as further optimization of the electronic controller. If they succeed in this, a new range of applications in the commercial and household sector could open up.

ACKNOWLEDGEMENTS

The authors would like to thank the partners of the SolarChill Partnership.
The authors would also like to thank the Danish Energy Agency for financial support to develop this new technology.

REFERENCES

Pedersen P. H., Katic I. Direct Drive Solar Coolers, 12th IIR International Gustav Lorentzen natural working Fluids Conference, Edinburgh, 2016.

SolarChill Partnership: www.solarchill.org.

WHO PQS website:
http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17

Pedersen P. H. , Maté J. “SolarChill Vaccine Cooler and Refrigerator: A Breakthrough Technology”, Industria Informatione, special international issue on refrigeration and air conditioning, UNEP, ATF and Centro Studi Galileo, 2007.

Pedersen P.H., Maté J. SolarChill technology, Solar powered direct drive refrigerators with hydrocarbon refrigerants. 9th IIR Gustav Lorentzen Natural Working Fluids Conference, Sydney, 2010.

Jensen, J.K., Moeller H., Katic I., Pedersen P.H., Markussen W.B. Comparison of compressor control strategies for solar direct drive refrigerators. The 25th IIR International Congress of refrigeration, August 2019, Montreal, Canada.