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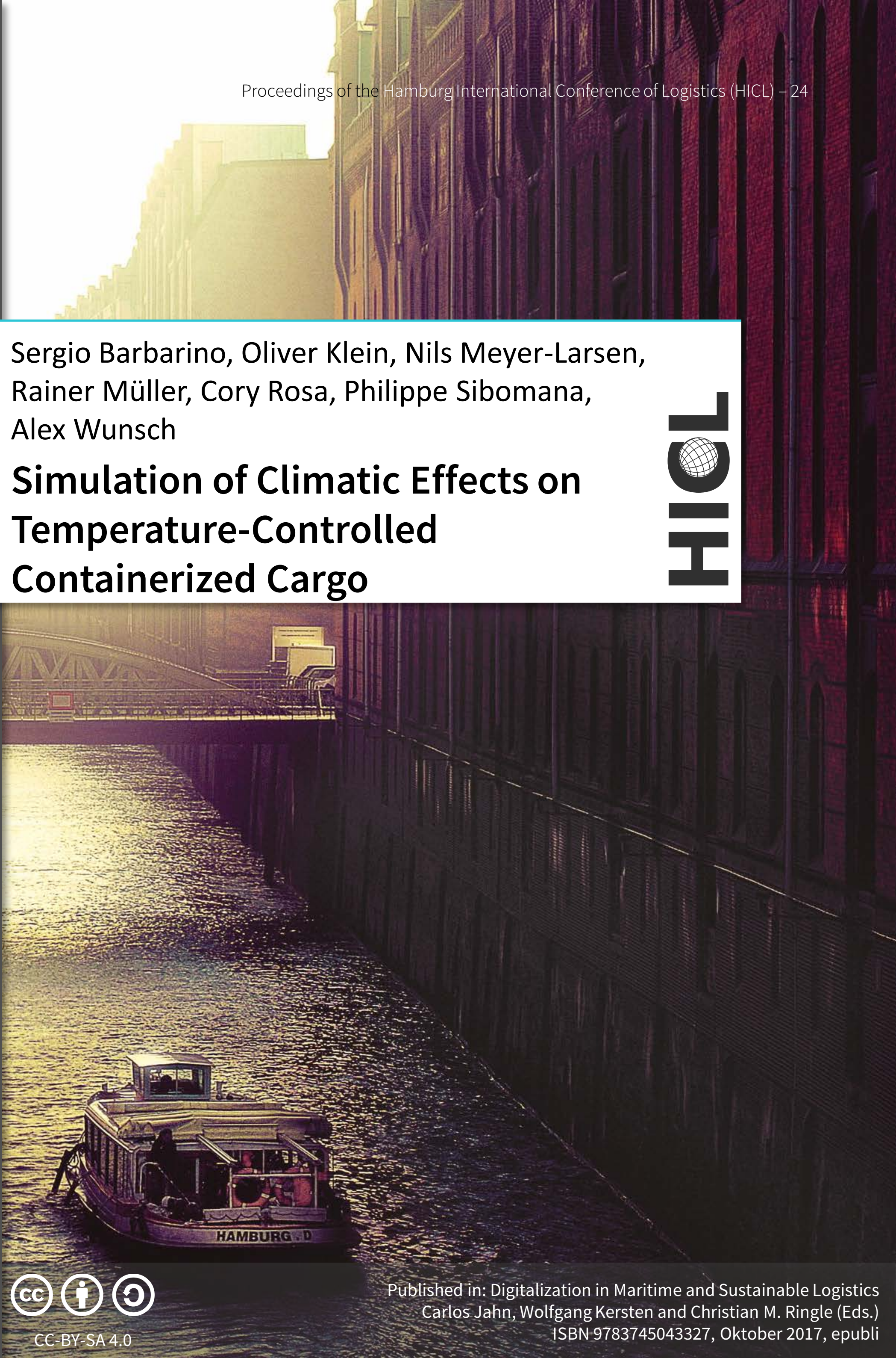

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Simulation of Climatic Effects on Temperature-Controlled Containerized Cargo

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This paper describes the so-called CORE Simulation Environment (CORE-SE), a scenario based simulation environment which was developed in the scope of the EU project CORE. CORE-SE in particular provides means for the simulation of logistics scenarios. It consists of a software agent platform that facilitates a multiagent-based simulation (MABS) approach. In MABS, the environment and the objects acting therein are modelled by a number of software agents. CORE-SE provides a platform to create and configure different simulation scenarios and finally "run" them by the emulation of the agents' behaviours in a coordinated and controlled way. CORE-SE, as described in this paper, has been applied in a specific supply chain sce-nario related to product integrity due to cargo temperature requirements where higher temperature (and solar radiation) could result in fluctuating product integrity in terms of quality loss and damage. During the simulated transport, climatic and weather-related factors like ambient temperature, ground temperature, solar radiation, and wind speed together with the resulting effects on the inner container temperature are simulated and respectively calculated according to the actual transport route of the container by usage of a climatic data model. The paper presents first results of the analysis, which are used to optimize the temperature control of the cargo, thereby better taking into account the mentioned external factors.

Keywords: Containerized Cargo; Container; Clima; Climatic Effects

1 Introduction

Procter & Gamble (P&G) has a large number of finished products and raw materials which do not normally require a temperature controlled supply chain, but suffer from extreme climatic conditions in summer/winter in some regions. There are no adequate and energy efficient solutions. Some technologies are based on diesel generators, resulting in very high cost and energy footprint. As some goods are temperature sensitive, truck and sea shipment are the means of transporting them to final locations. As a consequence, those trucks and containers might undergo severe climatic conditions throughout the journey resulting in damage or loss of product integrity.

This paper presents simulations and tests of a novel device unit performed in the scope of the CORE project (Core, 2017). The device will be loaded in normal standard dry shipping sea containers and allow passive and on demand cooling capability to the transported goods. This new solution – called ICECUBE, commercial name ChillX – will demonstrate a much more efficient solution which will reduce both the cost and energy footprint related to guarantying product integrity by keeping mild temperature conditions (30 °C) in trucks and containers during shipments. This will ensure the entire integrity of the full load throughout the end to end supply chain. The new solution is expected to allow a 30-40% overall carbon footprint reduction with respect to commonly used diesel generators.

This paper describes the usage of the CORE Simulation Environment (CORE-SE), a simulation framework for supply chains developed within the EU project CORE, and its application for simulations supporting the development of the ICECUBE system. In detail, the P&G tradelane from Spain to South Africa was modeled using a multiagent-based simulation (MABS) approach.

2 CORE Simulation Environment

For the simulation of the P&G simulation scenario the CORE Simulation Environment (CORE-SE) is used, in particular providing a computer-aided model that calculates all relevant ambient conditions throughout a shipment as a function of the container's location and the time of year based on historical data. CORE-SE consists of a software agent platform that facilitates a multiagent-based simulation (MABS) approach and provides means for the simulation of logistics scenarios.

In MABS, the environment and the objects acting therein are modelled by a number of software agents. CORE-SE provides a platform to create and configure different simulation scenarios and finally "run" them by the emulation of the agents' behaviours in a coordinated and controlled way. By usage of CORE-SE software developers are able to implement specific simulation scenarios of real operational conditions of secure supply chains with a special focus on resilience and controls in case of disturbances. The Scope of the simulation in the P&G demonstration is composed of:

- Assessment of the impact of weather conditions (e.g. temperature, solar radiation) on the temperature inside the container and the goods, cooled by the ICECUBE system
- Assessment of the impact of disturbances in the supply chain (e.g. strike in a port) on the temperature inside the container. In particular: what is the impact on the temperature of the goods if the container has been stopped due to a disturbance (e.g. strike in a port) for several days in an area with high temperature and high solar radiation impact?
- Overall goal is to simulate worst case situations in order to test the limits of the ICECUBE system, if it is capable of ensuring the product integrity even in worst case scenarios.

CORE-SE simulates the P&G tradelane including data on ambient temperature, wind speed and solar radiation incident during the transport of the container. In addition, during the transport events can occur which could lead to a delay. These events could be logistical delays, e.g. traffic jams during truck transport, Customs stops or other events (e.g. strike in a port). A delay could lead to a longer transportation time. Thus, longer exposure to higher temperature could be possible.

For each simulation run CORE-SE creates a CSV file which contains the following data:

- Hour
- Ambient air temperature
- Temperature of the surface below the container
- Solar radiation incident upon a horizontal surface
- Solar radiation incident upon the left wall of the container

- Solar radiation incident upon the right wall of the container
- The ambient wind speed relative to the container
- Geo-Position (latitude, longitude)

3 Climate data

The climate data used in the simulation is based on data from the ERA-Interim climate reanalysis (Dee, 2011) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

ERA-Interim is a still ongoing global data set describing the recent history of the atmosphere, land surface, and oceans, containing climate data from January 1979 to present. It is created by combining ECMWFs forecast models (IFS) and observations of many different sorts in an optimal way to produce a consistent, global best estimate of the various atmospheric, wave and oceanographic parameters.

The weather influencing the simulated container on the trade lane is based on the actual weather data on the location at the date in the year 2016. The year 2016 was used as base due to high temperatures in summer especially in Spain. To model the weather on the trade lane we use climate data for temperature, solar radiation, cloud coverage and wind speed. Especially ambient temperature, particularly solar effect, has significant influence on the container indoor temperature (Rodriguez-Bermejo, 2007). A similar methodology was applied by (Horak, 2016) to calculate the cabin air temperature of parked vehicles in summer conditions. In the following the data fields of the climate data are described, including limitations and restrictions for the current development phase of the simulation model.

Ambient air temperature The modelled temperature profile is based on the ERA-Interim climate data for temperature. A maximum, a minimum and an average temperature is calculated from the weather data of the actual day, the previous day and the next day. These values are used to adjust a typical daily temperature profile (sinus curve). The measure unit of this parameter is Degrees Celsius.

Temperature of the surface below the container The temperature of the surface below the container depends on the ambient air temperature at the location, how long that place was exposed to the sun before and heated up, and the time since the container was dropped. The simulation is partly based on results presented in (Jansson, 2006). The cooling off is assumed to be a steady function. The measure unit of this parameter is Degrees Celsius.

Solar radiation incident The solar radiation incident is calculated in total for three sides of the container:

- Top of the container
- Left side of the container
- Right side of the container

For each side the calculation uses the following parameters:

- Sun radiation at the location
- The sun position at that time of day
- The cloud coverage
- Direction the transport vehicle is heading
- Angle of the container side facing to the sun

From these values combined with the sun position at that time of day are calculated hourly incident solar radiation in W/m^2 for the top, left and right wall of the container. It is assumed that the container is always on the top row of the transport vehicle with nothing shadowing it left or right and orientated in the same direction as the vehicle. For example, if the transport vehicle is heading straight west, the front of the container is also facing westwards, the left side facing south, and the right side facing north. The measure unit of this parameter is W/m^2.

The ambient wind speed relative to the container The wind speed is calculated from the Zonal (eastward) wind value and Meridonal (northward) wind value provided by the ERA-Interim on that location and day in the year 2016. The speed and direction of the wind is assumed to reflect the worst case scenario that the container is fully exposed to the wind and not shielded by any obstacles. The measure unit of this parameter is m/s.

4 D3 heat transfer model

The D3 heat transfer model was created in order to predict the temperature conditions within a specific container under a broad range of input conditions and ambient conditions the system may experience while in transit, which are provided by the CORE-SE simulation. This in turn facilitates the evaluation of various design alternatives in order to develop an optimal design, and also the simulation of the limits to which this design is applicable. While the heat transfer model itself is sophisticated, the principle behind it is simple. The model receives user-defined inputs and performs necessary calculations to translate these inputs into useful outputs. In essence, these inputs are conditions we want to simulate, while the outputs serve to answer the question whether, based on the input conditions, the ICECUBE system will provide satisfactory control of the payload temperature, and if so, how much thermal storage medium in the ICECUBE thermal battery, which is analogous to the charge available in an electric battery system, is required.

5 Tradelane description

The tradelane in question starts at the P&G manufacturing site in Mataro, Spain. The containers are transported by truck to the container terminal in Barcelona, Spain, where they are loaded on a feeder vessel and shipped to the container terminal in Algeciras, Spain. From Algeciras the containers are transported by sea vessel to the container terminal in Durban, South Africa. The final part of the voyage is done by truck to the P&G warehouse in Durban. Locations, transport modes and durations are described in table 1. Six days is a typical transit time between Barcelona and Algeciras on some lines (Shortseaschedules, 2017).

Table 1: Location, transport modes and duration

From	Destination	Modality Type	Duration
Manufacturing Site - P&G, Mataro (Spain)	Terminal, Barcelona (Spain)	Road	50 min
Terminal, Barcelona (Spain)	Terminal, Algeciras (Spain)	Sea (Feeder)	6 d
Terminal, Algeciras (Spain)	Terminal, Durban (South Africa)	Sea	17 d
Terminal, Durban (South Africa)	P&G Warehouse, Durban (South Africa)	Road	35 min

6 Results of the simulation

The simulation model has been validated. In particular the weather data have been validated by the ERA-Interim climate data and the transport flow have been validated with schedules and routing algorithms.

In total 4 simulation runs have been made which are covering two different time periods and two different settings concerning the loading time. The different periods have been selected in order to have maximum temperatures in Spain resp. South Africa. The different loading times (2 days and 5 days) have been selected in order to model disturbance in ports (e.g. strike in port):

- Start on 2016-09-07 with 2 days loading time. Simulation run with maximum temperatures in Spain and short loading time.
- Start on 2016-09-07 with 5 days loading time. Simulation run with maximum temperatures in Spain and long loading time.
- Start on 2016-11-16 with 2 days loading time. Simulation run with maximum temperatures in South Africa and short loading time.
- Start on 2016-11-16 with 5 days loading time. Simulation run with maximum temperatures in South Africa and long loading time.

While multiple trials were conducted throughout this development, one scenario was chosen specifically for a deeper assessment, as is conducted below. In this scenario, a 40 foot dry container is shipped from Mataro, Spain to Durban, South Africa. The simulated shipment departs on July 9, 2016, and arrives on August 21, 2016. It is assumed that there are delays in the outbound port resulting in a relatively long duration of shipment. Figure 1 and Figure 2 show the results of CORE-SE simulation. Respectively, they are plots of the ambient temperatures and solar radiation incident on a horizontal surface versus time. Figure 3 and Figure 4 show the results of the D3 model. Respectively, they are a plot of the container and product temperatures and ICECUBE mass expiry versus time, and a map containing labelled positions indicating the thermal battery charge level for 5 specific days during the journey.

Figure 3 shows 3 data series. The series “T,product” refers to the temperature of the payload while “T,container” refers to the temperature of the shipping container itself as a result of heat exposition from the ambient. “m,Deepchill” refers to the mass of Deepchill, the thermal storage medium inside ICECUBE, that expires as a result of the ICECUBE system actively cooling the payload to prevent it from reaching 35 °C, the critical temperature of the payload.

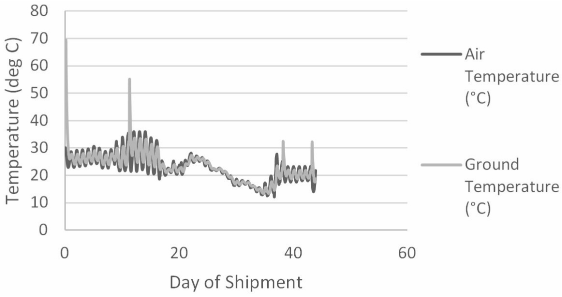

Figure 1: Plot of Ambient Temperatures versus Time

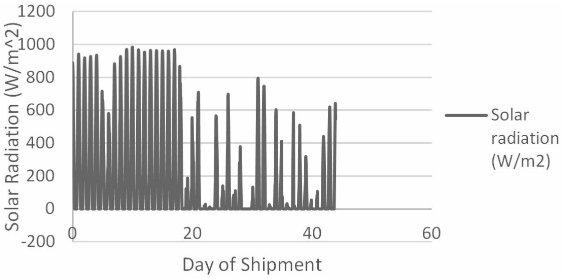

Figure 2: Plot of Solar Radiation Incident on Horizontal Surface versus Time

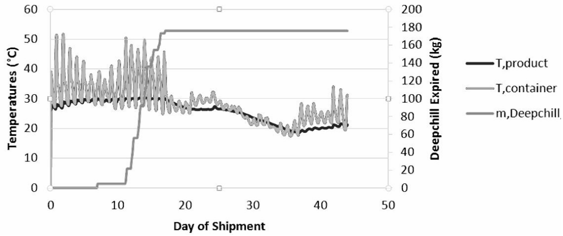

Figure 3: Plot of Container and Product Temperatures and Deepchill Expiry versus Time

7 Discussion of Results

Within the scope of this simulation, there are two objectives. The first is to develop a simulation tool that can reliably evaluate the performance of the ICECUBE system. This reliability starts from the use of realistic inputs (ambient conditions) and extends to an accurate evaluation of the system's performance based on these inputs. The second objective is to evaluate the system's performance for one specific case in which products are shipped on one of P&G's tradelanes. Both of these objectives will be discussed below.

The successful integration of CORE-SE with the D3 heat transfer model allows us to achieve the first objective. CORE-SE calculates ambient conditions based on real data recorded for recent years. The D3 model allows these inputs to be translated to useful outputs consistent with the trends observed in real test data. Concerning our second objective, we seek to answer two questions. These questions are:

1. does the ICECUBE system protect the payload from thermal damage, and
2. is there sufficient thermal energy available in the ICECUBE to do so during this shipment?

Referring to Figure 3, it is seen that the product temperature starts at 25 °C on the first day, and during the 7th day, this temperature has increased to 30 °C. At this point, the ICECUBE system begins actively using the stored thermal energy to cool the payload, as is visible from the increase in the data series "m,Deepchill". Over the course of the journey, roughly 180 kg of Deepchill are calculated to expire as a result of this active cooling. It can be seen that the products are successfully maintained below their critical temperature of 35 °C.

Figure 4 provides a visual representation of the thermal energy charge level available in the ICECUBE system. This figure accounts for Deepchill expired as a result of both active cooling and passive heat gained by the ICECUBE thermal battery. It is seen in Figure 4 that a substantial proportion of Deepchill expiry occurs by Day 23, which reflects the fact that the ICECUBE system is only active between the 7th and 17th days of the shipment. On the final day of shipment (Day 44), roughly 40% of the thermal energy is seen to remain. Therefore, we conclude that there is indeed sufficient thermal energy stored in the ICECUBE system to protect the payload from experiencing thermal damage.

Figure 4: Map of Shipment with Labelled Thermal Battery Charge Levels for Specific Days

8 Construction and first tests of a prototype

A half scale prototype of the ICECUBE device was designed, constructed and tested from both a thermodynamic and operability point of view. The first test validated the concept efficiency in cooling P&G loads over a long period of time. The second test focused on user case of operability and validated the “easy to use” concept of the prototype. Some improvements are needed to make the concept light and easier to use.

Figure 5 and 6 show a sketch and a picture of the ICECUBE prototype, which was used for demonstration and testing in order to prove the feasibility of the concept and validate the simulation results. Although first results are existing, a respective detailed analysis is not available to date. With regards to the lower carbon footprint emission, an initial estimate measurement of the baseline data for carbon footprint was performed. From the demonstration runs performed, the greenhouse gas reductions achieved have been projected to be reduced by 44% (from baseline of $71\,000\,\mathrm{kg\,a^{-1}}$ to $39\,000\,\mathrm{kg\,a^{-1}}$, based on an average of 250 trips per year). These promising first results need to be validated in further demonstration runs.

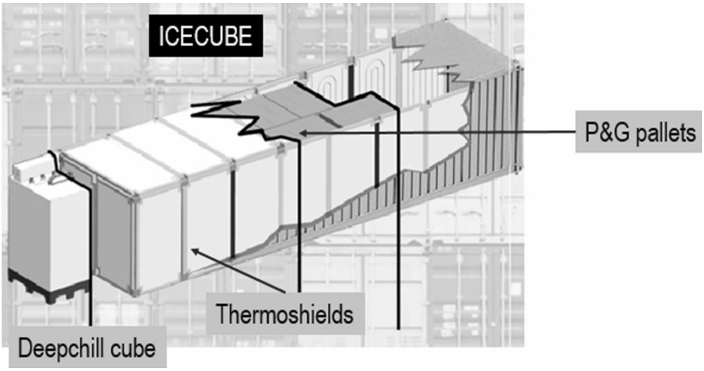

Figure 5: ICECUBE system

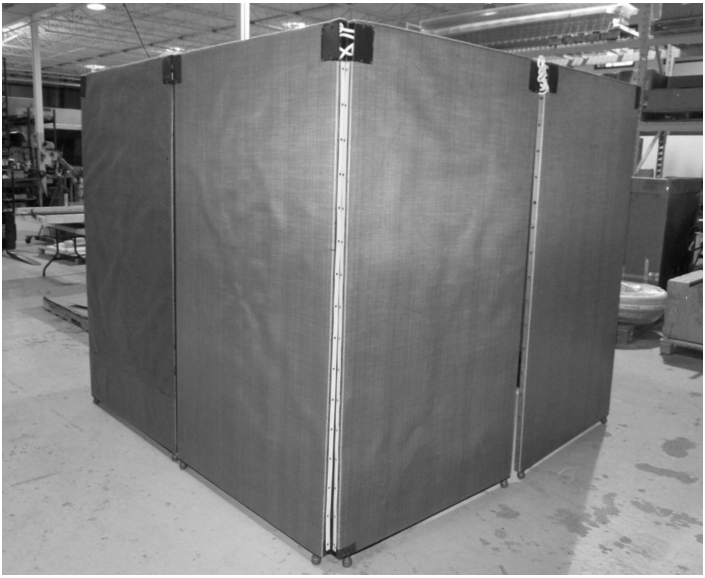

Figure 6: Half scale prototype of the ICECUBE system

9 Conclusions and outlook

The investigation presented in this paper has two objectives. The first was to develop a simulation tool that can reliably evaluate the performance of the ICE-CUBE system. This was accomplished by successfully performing an integration between the CORE Simulation Environment with the D3 heat transfer model. The second objective was to use this tool to perform one such evaluation for a shipment of products from Spain to South Africa. This was completed, and the ICECUBE system was concluded to successfully control the payload temperature, and to do so by using roughly 60% of its total thermal storage capacity. From first demonstration runs with a prototype, the greenhouse gas reductions have been estimated to be reduced by about 44%. These promising first results need to be validated in further demonstration runs.

In the current simulation model following assumptions have been made which have to be improved in next versions. By now disturbance can be modelled in terminals only on an abstract level. In detail, the loading time of the vessel can be set as parameter for each simulation run in order to test the impact of different events (like strike in a port). In later versions this will be fully integrated including random distribution for different events at different locations. In addition, climate data from 2016 only has been used. It has to be analysed if more realistic data could be retrieved if a longer time period would be used. Furthermore, in the current simulation the position of the container is on top of the vessel. Sun radiation and wind have impact from all sides, and the orientation of the container to the wind has not been identified, resulting in the simulation results to provide a worst case scenario. The simulation can be improved in future versions, possibly also taking into account effects by the coloring of the container, based on results presented in (Smith, 2003).

Acknowledgements

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