Compact Energy Efficient Dryer

Acronym: Engendo

January 2024

Projectleider: Rick Kirpestein (ISPT)

Programma Director: Peter de Jong (ISPT)

Consortium partners:

Avebe – Corbion – Givaudan

UCLouvain – UTwente - ISPT

Format final report

(confidential version with public summary)

Project Number RVO and/or ISPT(-TKI)	TKI19-Engender / projectnr. ISPT DR-50-18
Project Title + Acronym	Compact Energy Efficient Dryer (Engender)
Secretary (penvoerder)	ISPT
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Name project leader	Rick Kirpestein
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Project start	1-6-2021
Project original end date	1-6-2023
Project final end date	1-12-2023 after granted Request for Change by TKI

Overview Key Performance Indicators

KPI	Description
1. Organisation/ Coordinator	Institute for Sustainable Process Technology
2. Project number	DR-50-18
3. Project titel / acronym	Compact Energy Efficient Dryer (Engender)
4. TRL at closure, main category	4-5
5. TRL at closure, Detail category	4-5
6. Project succes	The project was not completed yet and is officially closed on 1st of December 2023. However, research activities by UCL will continue until April 2024 at UCLouvain own expense and any results will be disseminated by ISPT. The test program provided insights during shorter test runs in the window of operating conditions and in the stability of operation. Start-up and shut-down procedures were optimized and fouling conditions further investigated leading to modifications in inlet conditions. The test run length could also be extended. Powder/air separation, asymmetry in the flow pattern and emptying the RMD requires further optimization.

KPI	Description
	Modifications were also introduced to finetune the countercurrent flows to create a more ideal vortex. This was done with help of computational fluid dynamics (CFD) simulations by University of Twente to optimize the temperature zones in the drying chamber. Modifications are still ongoing to come to longtime experimental runs and further finetuning.
7. Follow-up	Follow-up is under investigation by finding an equipment builder that will be prepared to invest in a demo unit. For a follow-up new equipment with a simplified design and easy maintenance plus good auxiliary equipment (pump, blower, compressor, safety facilities, platform position) will be of essence to take the vortex technology to the required level.
8. Number of realised peer-reviewed publications	1
9. Number of peer-reviewed publications	2-3
10. Number of realized non-peer-reviewed publications	3
11. Number of filed patents	Not during this project, however for the former Radial Multizone Dryer project a patent was filed in 2018 with patent number PCT/NL2018/050284 by UC Louvain.
12. Number of granted licenses	none
13. Number of prototypes	none
14. Number of demonstrators	none
15. Number of spin-offs/ spin-outs	none
16. Number of new or improved products/processes/services introduced	Modification the hot air inlet distribution system, and liquid atomization system.
17. Impact	Based on calculations by TNO (former ECN) for the former RMD project in 2018, and based on calculations arising from both experiments and CFD work the gain in energy efficiency with a functional compact energy efficient dryer based on counter current drying will be 20%-40%.

Content - Final report

1. PUBLIC Summary

Spray drying is used in the food industry to transform food and dairy products into powders to preserve taste, smell and all nutritional aspects. It also guarantees product quality for a longer period of time and facilitates easy transport of products. Spray drying is, however, an energy intensive technology which consumes 15% of the overall energy consumption within the Dutch industry. The ENGENDER project was aiming to realize a breakthrough in drying of food ingredient materials using a new compact energy-efficient drying technology, the Radial Multizone Dryer (RMD). The RMD combines high-G force and multizone operation to intensify spray drying and offers a cost and energy efficient spray drying solution. Compared to standard spray drying technologies, the RMD enables lower footprint of equipment at equal drying capacity and related reduction of Capex and Opex. The equipment size is reduced by at least one order of magnitude. The dryer can significantly reduce the air consumption and exhaust air flow, but also reduces water use in the cleaning process (CIP) as there is less equipment surface to clean.

In the Engender project the RMD technology was further developed at pilot-scale for design rules for industrial demonstration. The expected energy savings were estimated up to 20-30% compared to conventional spray drying and to be confirmed for a selected set of model systems, that is, test materials.

The project has been building on results from previous projects that developed the RMD concept and in which an RMD apparatus was designed and tested at the lab scale and at the pilot plant scale for the specific needs of Friesland Campina, which focused on milk spray drying and gradual scale-up. Efficient drying is to be achieved by combining radial multizone and high-G force operation. The radial multizone operation allows to feed hot air in the radially central zone of the chamber where the droplets are injected and to feed air of lower temperature in the periphery where the particles are recovered. High-G force operation is achieved by making use of vortex chamber technology. The mild temperature air is injected through a number of vortex chamber inlets to generate a rotational motion and to control the axial motion of air in the drying chamber. Droplets injected in the chamber undergo a fast initial drying upon contact with the hot air and are under the action of the high-G force rapidly discharged to the mild temperature periphery for final drying and recovery.

In the ENGENDER project, the existing pilot plant unit was used to carry out spray drying experiments. The experiments were aimed at confirming the flexibility of the RMD technology and at optimizing the operating parameters and details of the design together with industrial partners Avebe, Corbion and Givaudan. Long-time testing by University of Louvain was planned for this project. The test program did allow us to gain insights during shorter test runs in the window of operating conditions and in the stability of operation. Start-up and shut-down procedures were optimized and fouling conditions further investigated leading to modifications in inlet conditions. The test run length could also be extended to hours instead of minutes. Powder/air separation and emptying the RMD requires further optimization.

Modifications were also introduced to finetune the countercurrent flows to create a more ideal vortex. This was done with help of computational fluid dynamics (CFD) simulations by University of Twente to optimize the temperature zones in the drying chamber. Modifications are still ongoing to come to longtime experimental runs and further finetuning.

The energy efficiency was investigated and based on experiments and simulations led to the conclusion of an improved energy efficiency of at least 20 % compared to conventional spray drying.

The operating principle is more energy efficient. The savings estimate is realistic, although scaling up risks will have to be accounted for.

In this context, we see two major challenges. The complexity of the current design makes scale-up and stable operation difficult. This has different reasons; the main one being the number of different airflows.

Recommendation is to use the available knowledge to create a simpler design. Product quality remains a concern. In particular, the exposure of dry product to hot air poses a risk here. This entails very high requirements for separation. This ties-in with the design question on the first point and places high demands on the droplet size distribution (when sprayed) and the particle size distribution of the resulting product. Technology is available to control this. It will have to be an integral part in a new, improved and simplified equipment design. Involvement of an industrial equipment supplier/manufacturer is therefore a pre-condition for any new design.

The conclusion is as a next step towards commercialization of the technology that scaling-up and building a new simplified design based on learnings from the Engender project will be necessary.

2. Introduction

The follow-up of the Radial Multizone Dryer (RMD) project was executed because of promising results from a first series of tests with the newly constructed pilot plant, i.e. the successful and repeated production of good quality milk powder during ca. 10 min test runs achieved quickly after taking into service the RMD pilot. A full investigation of the window of operating conditions was not possible in the 2.5-year RMD project, mainly because design, construction and commissioning of the RMD pilot was far more complex than anticipated. Peripheral equipment, such as air compressors and air heaters, had to be modified as well and in certain cases acquired. Furthermore, start-up procedures had to be developed and details of the design modified following insights gained from the first milk spray drying tests. Therefore, insufficient tests and in particular long-time tests could be carried out to do research on all aspects of the RMD.

Three industrial partners Avebe, Corbion and Givaudan have been partners in the follow-up Engender project for validation of their model systems and further development of a compact energy efficient dryer. Only milk spray drying had been studied, and the diversification of the model systems would have an overall positive effect on the research since specific product properties reveal details on the particle trajectories, the drying conditions encountered and the flow pattern in the dryer, as well as on the operating procedures.

The RMD technology is considered a promising technique, on the one hand because of the significantly reduced volume requirements and related advantages in terms of both Capex and Opex and in terms of safety, on the other hand because of potentially superior product quality and energy efficiency.

During the execution of the Engender project, however technical issues both within the design of the compact RMD dryer as well as in auxiliary equipment (compressor, blower) had to be resolved. With support of UTwente modifications have been executed on the original dryer, operating conditions and procedures for further optimization and efficiency on:

1) The hot air inlet distribution system;

2) The vortex chamber diameter-to-length ratio;

3) The liquid atomization system.

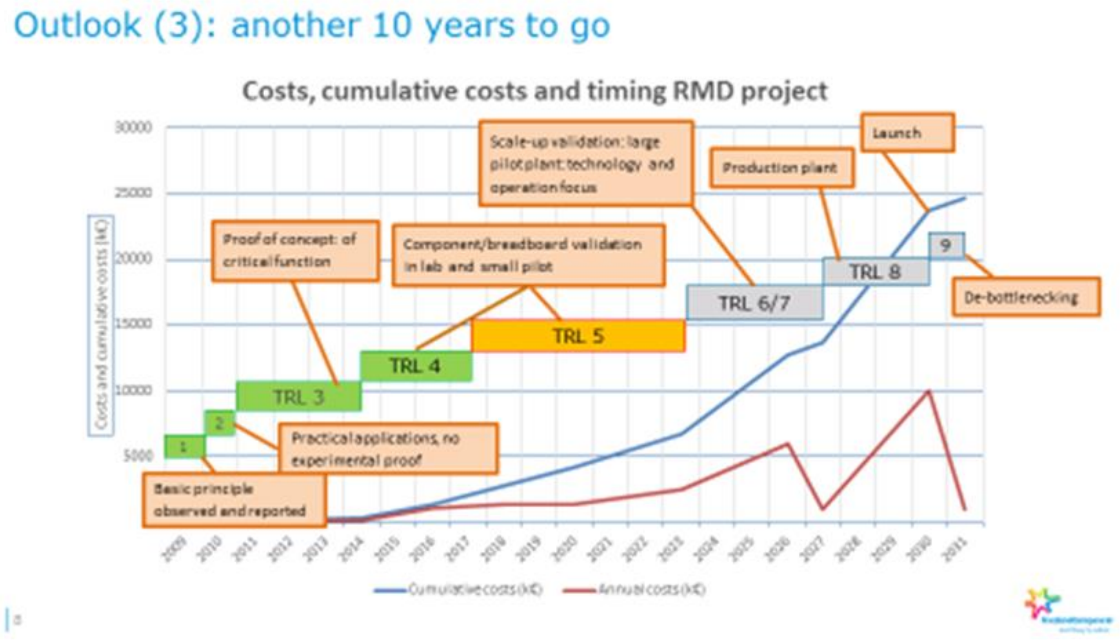
This allowed the pilot installation to run now for more than 1 hour, before design modifications as suggested by UTwente were implemented. A large set-back to the project was the leave of an experienced researcher, which meant a new researcher had to be recruited and trained from zero on a complex technology set-up. We concluded that it is needed to take learnings to a to-be-constructed radial multizone dryer, where an equipment builder will have to function both as partner & co-designer to be able to run further experiments to improve fundamental insight.

3. Objectives

The Radial Multizone Dryer (RMD) combines high-G forces and multizone operation to intensify spray drying and offer a cost and energy efficient spray drying solution. In particular, compared to standard spray drying technologies, the RMD aims at:

- Lower footprint of equipment at equal drying capacity and related reduction of Capex and Opex
- (equipment size reduced by at least one order of magnitude).
- Improved energy efficiency estimated at 20-40%.
- Significant reduction of air consumption and of exhaust air – such exhaust air, e.g. from spray drying flavours or fragrances, may be heavily polluted and needs treatment. Reduction of the drying air quantity will reduce efforts in exhaust air treatment.
- Reduced water consumption in cleaning process (CIP) as a result of the lower footprint (less
- equipment surface to clean).
- Same or improved product quality. At least cost neutral compared to standard spray drying process (same manufacturing cost per kg of product).

The long-term objective of scaling-up of the Compact Energy Efficient Dryer is implementation of the technology by 2031. The project is to be qualified as Industrial Research (IO) with validation of several model systems.



Outlook (3): another 10 years to go

Fig.1 Outlook on development Compact Energy Efficient Dryer until 2031

The Objectives of the Engender project were:

- a. Fixing design and start-up bottlenecks
- b. Product quality confirmation with various model systems
- c. Determining the influence of the operating parameters on the product quality and drying efficiency
- d. Analyzing and optimizing the energy efficiency of the RMD via experiments and CFD
- e. Preparation of scale-up for the construction of RMD demo plant

These objectives of the different work packages are described in Chapter 3.

Challenges and benefits

The calculations from the RMD project were based on a range of assumptions and estimations. Below these are discussed in terms of their potential benefits and potential challenges for the Engender project.

Potential challenges

Mixing of hot and cold air

The current energy efficiency calculation assumes no mixing of various injected air flows occurs. It is likely some transfer or mixing of the flows occurs. For small amounts the impact will be negligible: the hot flow might become somewhat colder but if the heat from the medium is also recovered and increased due to the mixing, the heat is just recovered from another stream. Significant mixing, especially between the hot, moist flow and the cool, dry flow, can cause issues such as too high humidity or even temperature of the cool flow causing stickiness problems as well as reduced heat recovery from the hot flow, especially when air recycling options become limited when there is significant transfer to the cool, dry flow.

Energy use of the compressor

In the current calculation a minimal work input calculation for air at ambient temperature combined with a factor 2 multiplier to correct for inefficiencies, has been used to estimate the compressor energy use. When recycling hot air, the energy use of the compressor will increase proportional with the air density. Similarly, if a higher pressure drop than the assumed 100mbar is required, this will increase electricity use albeit the additional heat demand (from gas) will be reduced.

75% heat recovery estimate could be too optimistic

Using air recycling, it is relatively easy to recover considerable amount of heat as all heat in the recycled air is recovered. Note that some of the hot flow has to be removed in order to remove the water evaporated in the drying process. Using air to air heat exchangers, recovering 75% of the heat is much more challenging: it requires relatively large and therefore expensive heat exchangers. The feasibility of this option will/should be verified in the CAPEX estimate & comparison.

Energy efficient conditions not necessarily optimal for product quality

The operation window of the vortex chamber is determined by the interaction of the three air flows. Creating the vortices necessary for drying and providing high product quality will not necessarily be the conditions optimal with regards to energy efficiency. However, the used conditions in the current calculations are actual operating conditions for the vortex chamber.

Potential benefits

Reduced pressure ratio of the compressors

Currently 100mbar pressure increase is assumed for the compressor. A reduced pressure drop will not only mean the electricity use of the compressor is reduced and therefore has a positive impact on the OPEX, also the CAPEX will be reduced as more simple and less powerful compressors will be needed.

Improved product quality

The drying process of the vortex chamber allows separation between the air flow containing the product and the airflow containing the drying heat as well as retaining its moisture, it can improve product quality or even allow to dry products that would in standard spray dryers become too sticky.

Compactness/reduced footprint

The high temperature reduces residence time for particles to dry and therefore the system can be made more compact compared to a traditional spray dryer. Provided care is taken this space benefit is not counteracted by the additional compressors and – if needed – air to air heat exchangers, it can have a smaller footprint allowing to increase drying capacity per m^2 of (expensive) food-grade workspace.

No need for cyclones

The vortex chamber has the potential to catch also the fines removing the need for a cyclone. If this would proven to be correct, this will reduce overall costs and footprint.

CO_2 taxes

One of the challenges of the vortex chamber is its electricity use in the compressors as the energy costs for electricity are considerably higher than for heat from gas. With the need to reduce CO_2 emissions, it is expected that the price for the CO_2 emissions associated with gas use will become more and more expensive thereby making electrically driven dryers more attractive option for the future. For the vortex chamber this means its electricity use for the compressor is no longer impacting OPEX negatively.

The objectives of the work packages were

(1) Fixing design and start-up bottlenecks

The small RMD pilot at UCLouvain is fully operational (see below picture). Tests with milk spray drying have revealed that certain details of the design can be improved. The hot air distribution is not yet perfectly symmetrical and some deposits inside the hot air inlet are observed. Minor modifications in the hot air inlet design, the position of the spray nozzles and the operating parameters will be considered to improve operation. Optimization of the start-up procedure also needs to be addressed. The unit is started and heated up after which water is sprayed and evaporated in the chamber until stable and appropriate conditions for spray drying are reached. The latter is verified by detailed temperature measurements inside the drying chamber. The next step in which water feeding is switched to milk feeding is critical. After switching to milk, the temperature in the chamber will vary and reaching the new, stable temperature field takes a certain amount of time during which fouling can occur. The feed air temperatures and the liquid feed rate can be adjusted when switching from water to milk to account for the dry matter content and, hence, smaller fraction of water to be evaporated. But the characteristics of the milk droplets are also different from those of the water droplets and this is more difficult to account for. The data will be also used as input parameters for the CFD optimization and scale-up study. With the insight gained, operating procedures will be optimized to prevent fouling during start-up and during long-time operation. The robustness of the start-up procedure with selected other model systems and with respect to (small) variations in working conditions will be tested.

Image 1: The new RMD pilot plant at UCLouvain

(2) Product quality confirmation with various model systems

So far, pilot plant tests focused on milk spray drying. Milk is known to be challenging to spray dry and was considered as a worst-case model system for the RMD development so far. Spray drying other model systems as well is, however, essential to gain insight in the flexibility of the RMD and in the influence of the operating conditions on the product quality for such model systems. Therefore, detailed information about spray parameters (droplets SMD, D10, D90, distribution, velocity) for various feeds will be obtained by means of a state-of-the-art PDIA atomization test rig. Furthermore, detailed analysis of the spray drying results – product characteristics, eventual deposits in the chamber – will allow to gain insight in the complex flow pattern and the temperature trajectory seen by the particles. The industrial project partners have particular interest in following model components:

- Avebe: potato starch derivatives
- Corbion: lactic acids derivatives or a model system
- Givaudan: encapsulated flavours or a model system.

(3) Determining the influence of the operating parameters on the product quality and drying efficiency

Air is fed at different locations in the RMD. Air flow rates and feed temperatures can be varied and the influence on the drying efficiency and the product quality analyzed. The main air streams are the hot air that is fed axially in the radial center of the chamber, a counter-current air stream injected via the sleeve and surrounding the droplets that are injected into the chamber, and the mild temperature air injected in the two vortex chambers at both ends of the main drying chamber and the top end of the cyclonic extension. Furthermore, a rotational component is given to the hot air and air coming from the sleeve in order to generate a sufficiently wide opening of the hot air and to prevent fouling of the hot air inlet and of the nozzle tips. Succesful milk spray drying tests have been carried out for given operating parameters, but the influence of the operating parameters on the drying efficiency and product quality needs to be understood in more detail. A combination of experimental and CFD work will allow to gain the needed insight. The analysis of the product quality will be in close collaboration with the industrial partners. Physical and chemical properties of the produced particles will be considered. Reference data on currently used technologies and commercial product properties will also be provided by the industrial partners.

(4a) Analyzing and optimizing the energy efficiency of the RMD via experiments

The capability of the RMD to use hot drying air and ensure a very short contact time between the particles and this hot air, combined with high slip velocities and related efficient mass and heat transfer, allow significant process intensification leading to drying chambers that are more than one order smaller in volume than conventional spray dryers. Efficient use of the hot air requires sufficient contact between the hot air and droplets on their way through the chamber. This is affected by the concentration of droplets that can be generated in the radially central zone of the chamber and by the flow pattern. Mixing of hot air and mild temperature air also has to be avoided, both for energy efficiency and to prevent product degradation. Both experimental data and CFD simulations confirmed that within the RMD distinct and sufficiently large hot air and mild temperature air zones can be generated, allowing for efficient usage of the hot air and preventing product degradation – an essential feature of the RMD technology. Based on the experimental data, the energy efficiency of the RMD will be analysed for comparison with existing technologies. The data for selected model systems and for various operating conditions (see WP3) will also allow evaluating the robustness of the energy efficiency of the RMD.

(4b) Optimizing dryer performance via multiscale and multiphase simulations

During the course of the past projects, a CFD model was developed [1] [2] [3]. It is based on a Lagrangian-Eulerian problem formulation where the description of the droplet/particle phase is done in the discrete phase using numerical parcels and the gas flow is modelled using continuous phase. Simulations were focused on pure water particles evaporation and milk spray drying. For the latter, the CFD model of the particles was combined with the Reaction Engineering Approach to account for the intra-particle temperature gradient and delayed evaporation of the moisture trapped inside the droplet., see Fig. 2 for the drying trajectory of various particles. In this project, the aim is to extend the existing model to new feeds and use it as a tool for providing details into drying behaviour of the RMD and to final optimization of the drying conditions and scaling-up.

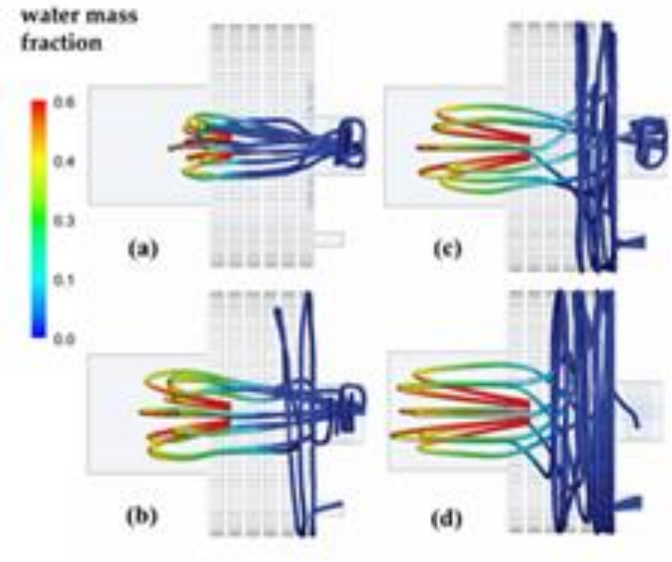


Fig. 2 Penetration depth and trajectory various particle size; (a) <30 µm, (b) 30-45 µm, (c) 45-60 µm, (d) 60-75 µm

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[1] *Rahman, J.U. , Pozarlik, A. K., Tourneur, T., de Broqueville, A., De Wilde, J. , & Brem, G. (2021). Numerical Study toward Optimization of Spray Drying in a Novel Radial Multizone Dryer. Energies, 14(5), [1233];*

[2] *Rahman, J.U. (2018). Redesign of novel lab scale vortex chamber for drying of milk sprays. PDEng Thesis, University of Twente;*

[3] *Baiazitov, I. (2018) Design of the pilot-scale vortex chamber spray dryer, PDEng thesis, Unviersity of Twente.*

(5) Preparation of scale-up for the construction of a RMD demo plant

Using the obtained test data and the developed multiscale simulation model, further scale-up of the RMD to a demo-unit will be prepared. The objective is to provide a preliminary design in terms of capacity and equipment size. The detailed design will be addressed in a follow-up project.

(6) Project management and Dissemination

Technical supervision and Secretary (Penvoerder) of the project. Quality assurance, risk management, internal communication, capacity building monitoring and assuring of the project progress. Connection with the Drying and Dewatering cluster and industry network. Knowledge dissemination and exchange, coordination and support according to RVO requirements.

4. Project execution

a. Work breakdown structure

Anticipated Results

Referring to the objectives as defined above:

(1) Fixing design and start-up bottlenecks

- Optimized RMD design and operating conditions.

- Understanding of droplets characteristics and nozzle selection from PDIA atomization tests with various model systems.

- Robust start-up procedures that prevent fouling during start-up and allow long-time operation.

2) Product quality confirmation with various model systems

- Confirmation that following model components can be spray dried successfully in the RMD pilot plant:

- potato starch derivatives (Avebe)
- lactic acid derivatives or a model system (Corbion)
- encapsulated flavours or a model system (Givaudan)
  where successfully means:
- without significant deposits on the chamber walls, nozzle tips or protective sleeve
- without visible degradation of the product
- with at least 10 min continuous feeding of the model component.

- Data on working operating conditions for the various model systems.

(3) Determining the influence of the operating parameters on the product quality and drying efficiency

- Data on the influence of the operating parameters on the product properties and drying efficiency for selected model systems, where operating parameters include:

- feed flow rates and temperatures of the hot air, the air injected via the protective sleeve and the air injected in the various vortex chambers in the main drying chamber and the cyclonic extension
- axial position of the spray nozzles and their protecting sleeve
- start-up and shut-down procedures.

Product properties include:

- physical properties, such as the particle size distribution, bulk density, coloration, degree of agglomeration, sintering, and solubility
- chemical / nutritional properties, such as the protein content and the degree of oxidation
- and will need to be analysed for the particles recovered via the different solids outlets.

The drying efficiency will be evaluated based on the measured feed flow rates and temperatures and the measured exit temperatures and air humidity.

- The RMD pilot plant test data will also be used for the development and validation of the multiscale RMD simulation model. Detailed temperature profiles inside the RMD during dry operation, during water feeding and evaporation and during spray drying of selected model components will be measured for that purpose.

(4a) Analyzing the energy efficiency of the RMD

- RMD pilot plant data with selected model systems on the energy efficiency and on eventual effects on the drying efficiency and product properties.

- Detailed analysis of the energy efficiency of the RMD pilot plant unit and recommendations for further optimization.

- Evaluation of the robustness of the energy efficiency of the RMD with respect to the model system spray dried and the operating conditions applied.

- Updated comparison with existing spray drying technologies.

(4b) Optimizing dryer performance via multiscale and multiphase simulations

- Multiscale and multiphase RMD simulation model coupled with Reaction Engineering Approach for selected model systems, including:

- drying paths of various droplets and feeds
- regions prone for product agglomeration/stickiness
- separation efficiency of small/big particles and their drying time
- Operational window for the investigated feeds

(5) Preparation of scale-up for the construction of a RMD demo plant

- Pre-design of a RMD demo unit with rough dimensioning for given capacity and selected model system and required energy efficiency improving measures.

(6) Project management and Dissemination

- Kick-off, Mid-term and Closure meeting
- Coordinating evaluation moment(s) for GO / NO-GO decision
- Carrying out the technical project lead
- Coordinating and sharing of confidential/non-confidential final reports
- Project data repository in MS Teams with dedicated project documentation for sharing of technical content between partners; reports, minutes, action and decision list, publications and presentations.
- Technical public project communication such as newsletters, poster, publication of scientific journal paper, contribution to scientific conference.

Connection to ISPT network/clusters via ad additional Focus group (Cluster Drying & Dewatering, ISPT) to share their technical experience and know-how, and will give their input to the project in combined meetings. Also these parties will be used for dissemination and continuation of the project

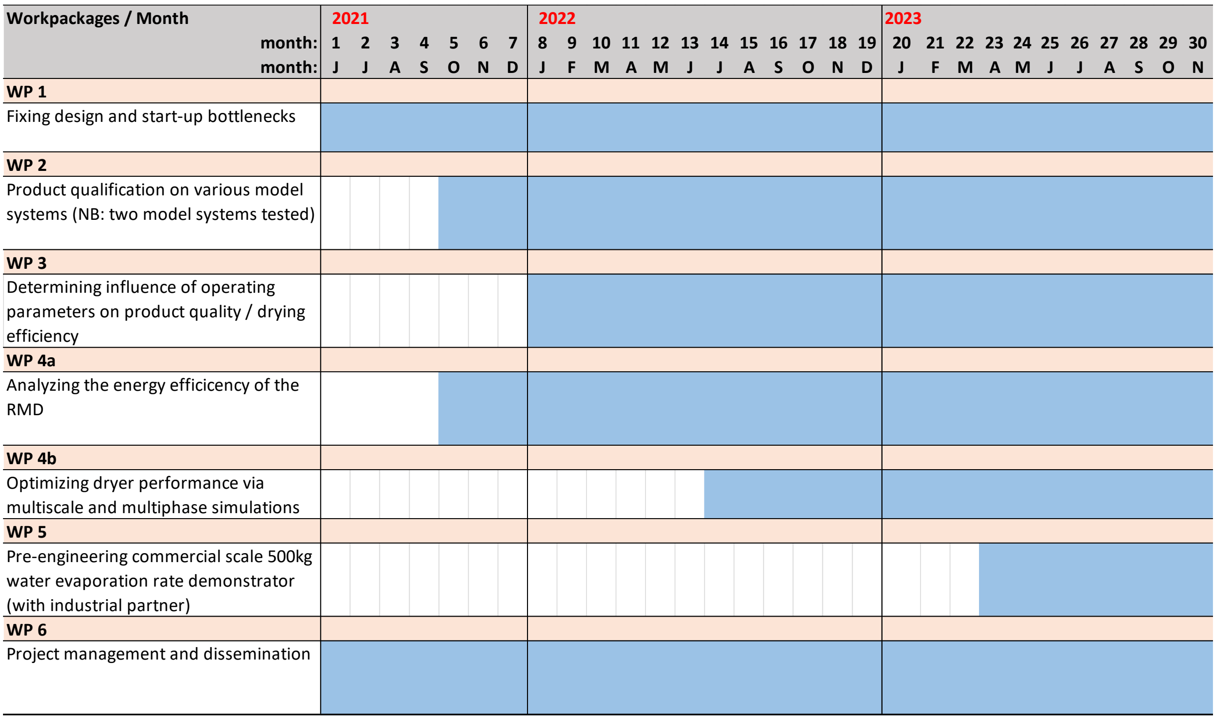
.4.1 Work breakdown structure and summary of work packages

	WP title / short description	Cat.	WP leader	Deliverables and milestones	Planning (start/ end)
1	Fixing design and start-up bottlenecks	**NEA**	UCLouvain	- Optimized and robust RMD design, start-up/shut-down procedures and operating conditions. - Start-up procedures that prevent fouling during start-up and allow long-time operation. - Nozzle selection based on experimentally measured atomization properties.	Months 1-3
2	Product quality confirmation with various model systems	**NEA**	UCLouvain	- Confirmation that following model components can be spray dried successfully in the RMD pilot plant: • potato starch derivatives (Avebe) • lactic acid derivatives or a model system (Corbion) • encapsulated flavours or a model system (Givaudan) where successfully means: • without significant deposits on the chamber walls, nozzle tips or protective sleeve • without visible degradation of the product with at least 10 min continuous feeding of the model component. - Data on working operating conditions for the various model systems (reference conditions for WP3).	Months 3-12
3	Determining the influence of the operating parameters on the product quality and drying efficiency	**NEA**	UCLouvain	- Data on the influence of the operating parameters on the product properties and drying efficiency for selected model systems, where operating parameters include: • Feed flow rates and temperatures of the hot air, the air injected via the protective sleeve and the air injected in the various vortex chambers in the main drying chamber and the cyclonic extension • Axial position of the spray nozzles and their protecting sleeve • Start-up and shut-down procedures. • Product properties include: physical properties, such as the particle size distribution, coloration, degree of agglomeration, sintering, and solubility • Chemical / nutritional properties, such as the protein content and the degree of oxidation and will need to be analysed for the particles recovered via the different solids outlets.	Months 11-18

				- The drying efficiency will be evaluated based on the measured feed flow rates and temperatures and the measured exit temperatures and air humidity. - The RMD pilot plant test data will also be used for the development and validation of the multiscale RMD simulation model. Detailed temperature profiles inside the RMD during dry operation, during water feeding and evaporation and during spray drying of selected model components will be measured for that purpose.	
4a	Analysing and optimizing the energy efficiency of the RMD via experiments and CFD.	**NEA**	UCLouvain	- RMD pilot plant data with selected model systems on the energy efficiency and eventual effect on the drying efficiency and product properties. - Detailed analysis of the energy efficiency of the RMD pilot plant unit and its robustness. - Recommendations for further optimization. - Updated comparison with existing spray drying technologies.	
4b	Multiscale and multiphase simulation for drying optimization	**NEA**	UTwente	- Tabularized data from atomization experiments (month 12) - Numerical model validated with experimental data of UCLouvain (month 15) - Report about drying operational window for various model components (month 20)	M12 M18-20 M1-20
5	Preparation of scale-up for the construction of a RMD demo plant	**NEA**	UCLouvain	Pre-design of a RMD demo unit, based on experimental and CFD data, with rough dimensioning for given capacity and selected model system and required energy efficiency improving measures.	M20-24
6	Project management and Dissemination	**IO**	ISPT	Technical supervision and Secretary (Penvoerder) of the project. Quality assurance, risk management, internal communication, capacity building monitoring and assuring of the project progress. Connection with the Drying and Dewatering cluster and industry network. Knowledge dissemination and exchange, coordination and support according to RVO requirements.	M1-M24

b. Planning

4.2 Gantt chart:



Workpackages / Month	2021							2022												2023										
month:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
month:	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N
WP 1																														
Fixing design and start-up bottlenecks	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 2																														
Product qualification on various model systems (NB: two model systems tested)					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 3																														
Determining influence of operating parameters on product quality / drying efficiency								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 4a																														
Analyzing the energy efficicency of the RMD					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 4b																														
Optimizing dryer performance via multiscale and multiphase simulations														■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 5																														
Pre-engineering commercial scale 500kg water evaporation rate demonstrator (with industrial partner)																							■	■	■	■	■	■	■	■
WP 6																														
Project management and dissemination	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

4.3 Status Deliverables

Deliverables	Team member	Status
WP1 **Fixing design and start-up bottlenecks**	UCL	**- Well-established and robust start-up / shut-down procedures** A number of the design and start-up bottlenecks have been addressed. **- Nozzle selection and spray characterisation** Nozzle selection based on experimentally measured atomization properties. Discussion with industrial partners about single-fluid nozzle use and eventually available nozzles – so far operation with two-fluid nozzles; at this point generating PSD below industrial target. **- Fouling prevented, also during start-up** Start-up procedures that prevent fouling during start-up and allow longer-time operation. Tests with duration of hours instead of minutes carried out successfully. **- Long-time operation made possible.** A problem remains asymmetry in the flow pattern in the chamber caused by the hot air and injected droplets cloud (partially) bypassing one another. A major part of the

		experimental test program had to be redirected towards solving this issue as it limited operation time to several hours and reduces the efficiency of the dryer. A new hot air inlet design has improved the symmetry.
WP2 **Product quality confirmation for the different model systems**	UCL	**- Data on required operating conditions for each of the model systems (reference conditions for WP3).** It was decided early in the project to switch from milk to **one** model component of general interest to the industrial partners – maltodextrin. Background for this was the need to investigate steady state operation (mass balance) endurance behaviour / product extraction and process yield. All tests were carried out starting from a solution of this model component. Produced powder quality was analysed and quality issues to be improved identified. **- Data on working operating conditions for the various model systems (reference conditions for WP3).** Data of different tests available – product quality was analysed, but not yet optimal and generally of too small particle size when compared to industrial application needs.
WP3 **Determining the influence of the operating parameters on the product quality and drying efficiency**		**- Data on the influence of the operating conditions on the product quality and drying efficiency with selected model systems.** Due to various problems with auxiliary equipment – two compressors that are used had to be repaired and finally replaced and the main air heater had to be fixed – it was not possible to rigorously study the influence of the operating parameters on the product quality. Next to that the experienced main process technologist took a different position in the middle of the project and had to be urgently replaced by an unexperienced new researcher who had to learn how to deal with this complex technology and set-up. As a result it was not possible to fully execute the significant number of planned trials. It was hard to recover from these setbacks within the only 2.5 year project duration. - The drying efficiency was further studied theoretically and by means of CFD modelling. Experimental and CFD data were compared to validate the model - The RMD pilot plant test data was used for the development and validation of the multiscale RMD simulation model. Detailed temperature profiles inside the RMD during dry operation, during water feeding and evaporation and during spray drying of MD12 were measured for that purpose.
WP4a **Analyzing the energy efficiency of the RMD**	UCL	- **Data on the energy efficiency of the RMD dryer for the different model systems** **- Comparison of the RMD energy efficiency with model predictions-** **and with currently used spray drying technologies and evaluation of energy efficiency gains.** The energy efficiency of the RMD unit was theoretically calculated and the assumptions at the basis of the predicted performance identified. The theoretical

		model predictions are in line with earlier calculations by TNO (former ECN) and experimental observations. At least 20-40% improved energy efficiency can be targeted. Comparison of the RMD energy efficiency was done via CFD simulations using value of the moisture content of the particles leaving the reactor. - Detailed analysis of the energy efficiency of the RMD pilot plant unit and its robustness. - Recommendations for further optimization were executed till a certain extend. Optimization recommendations were provided continuously during the duration of the project to improve the operationality of the experimental test rig. Some improvements due to failure of the auxiliary equipment around the test rig could not be tested. - Updated comparison with existing spray drying technologies was executed till a certain extend via comparing the energy efficiency with standard dryer.
WP4b **Multiscale and multiphase simulation for drying optimization** **-Tabularized data from atomization experiments (month 12)** **- Numerical model validated with experimental data of UCLouvain (month 15)**	UT	Viscosity measurements of the feeds investigated during the experimental campaign were done using Brookfield DV2+ PRO viscometer. Since the majority of the experiments were performed with maltodextrin DE12, this model compound was selected. The measurements were done for various preheating temperatures (20-75degC) and maltodextrin content (20-60 wt/wt%). Since direct spraying of the maltodextrin in the atomization test rig should be avoided, due to contamination of the test rig and difficulty with removal of the sticky content, the viscosity of the feed was matched using water-glycerol mixture. The viscosity measurements show that preheating of high maltodextrin concentrations to 75degC results in formation of a gel-like structures. Thus, it was advised to the project partners to not use it in that form. From the atomization experiments, it was visible that air atomization pressure, investigated in the range up to 7bar, has major effect on the droplet size and distribution of the droplets. However, after certain pressure the effect is diminished suggesting that this was the maximum energy which the spray could accommodate and further size reduction of the droplets is not visible (the limit of the SMD depending on the viscosity of the fluid was located somewhere between 12-13 mPas. Based on this work, it was advised to the project partners to reduce the atomization pressure in order to obtain droplet size representative to the investigated system. Data about atomization experiments is available, see also EngD report, chapter 5. Numerical model used in this research is based on the model developed and validated for different dryer configuration, see Rahman (PhD thesis of Umair Ur Rahman). The model was further qualitatively validated with the current configuration of the Engender dryer showing in general a good agreement with the experimental data. It should be noted, however, that due to failure of the auxiliary equipment during the experimental campaign, it was difficult to obtain a steady state operational conditions for direct comparison with the numerical computations. The numerical model was extensively used for the improvement of the operational parameters and for the changes in the geometry of the RMD dryer. The changes were related to: (i) reduction of the preheating temperature

- Report on drying operational window for various model comp. (month 20)		of the maltodextrin to avoid a polymerization process, (ii) reduction of the air atomization pressure to reduce the energy use in the system, and to avoid formation of spray with unrealistically small droplet size, (iii) redesign of the hot section of the diffuser to reduce the hot flow instabilities and oscillations, (iv) relocation of the solid outlet for small powder particles (S3) and regular solid outlets (S1 and S2), as well as additions of the solid outlet (S11) to improve the overall product recovery from the reactor, (v) closing solid outlet in the middle section of the reactor (S4) for efficient use of the heat and reduction of the hot air leak and (vi) increase the overall droplet size, as well as the total mass flow rate of the feed to optimized and rise the overall process efficiency. Most of the changes was also implemented in the experimental test rig showing a positive effect on the overall system performance. Yet, it should be stated that long duration experiments are needed to fully assess the implemented changes. Based on the numerical data, the improvements led to reduction of the amount of the particles leaving the reactor via the gas outlet from 19,5 wt/wt% to 11,6 wt/wt% and the total increase of the recovery of the product material from approx. 53 wt/wt% to full recovery. The calculations of the Energy Specific Consumption (ESC) show that the proposed configuration of the spray dryer is about 21% more efficient that currently used industrial spray dryers. The main effort of the simulations was to improve the operational ability of the test rig. Therefore, all calculations were done only for one model component, i.e milk (or maltodextrin as its representative). The calculations identified conditions at which good drying with full product recovery and high energy efficiency is possible. More details are available in the EngD report.
WP5 **Preparation of scale-up for the construction of a RMD demo plant**	UCL + Project leader	**- Dimensions and air and heating requirements for a future demo unit of a compact and efficient RMD dryer.** Following the experimental observations and CFD simulations, improvements to be made to the RMD design for a scaled-up version have been identified. The operating principle is more energy efficient. The savings estimate seems realistic, though with the (scaling up) risks. In this context, we see two major challenges: The complexity of the current design makes scale-up and stable operation in practice difficult. This has several reasons; the main one being the number of different airflows. Recommendation is to use the knowledge currently available to create a simpler design. Product quality is a concern. In particular, the exposure of dry product to hot air poses a risk here, so operating conditions should be further optimized/tested. This entails very high requirements for separation. This ties in with the design question on the first point and places high demands on the droplet size distribution (when sprayed) and the particle size distribution of the resulting product. Technology is available to control this. It will have to be an integral part of a new improved and simplified design. Involvement of an industrial equipment manufacturer is a pre-condition for any new design.

WP6 **Substantive technical supervision & Evaluation research results**	ISPT	- Kick-off meeting on 5th July 2021 - Mid-term Review on 21st November 2022 - Closure meeting 15th December 2023 - Coordinating evaluation moment(s) for GO / NO-GO decision - Carrying out the technical project lead was executed. - Sharing of technical content between partners; reports, minutes, action and decision list, publications and presentations. For communication and dissemination see chapter 9. - Coordination and sharing of confidential and non-confidential final reports. - Project data repository (protected intranet environment) in MS Teams dedicated project documentation for Engender project is present, up-to-date and will stay available after project closure. - Technical public project communication; publications will follow in Q1/Q2-2024 from UCLouvain (article(s)), final results in news item ISPT. - Connection to the ISPT network and clusters was ongoing during project execution during Drying program meetings. Presentations during Drying & Dewatering program of ISPT in 2022 and 2023. Poster presentation during NWGD Symposium 2022. Presentation during NWGD Symposium 2023.

c. Justifications for relevant changes with respect to project plan

Requested start date of the project was 1st of July 2021, as the former project Radial Multizone Dryer had 30th of June 2021 as end date of the project. However, in the grant of TKI Energy the start date has been consolidated on 1st of June 2021.

Request for Change submitted on 7th March 2023 to TKI Energy for prolongation of the project with 6 months until 1 December 2023, due to PhD researcher of UCLouvain quitting his job per 1st of January 2023 because of personal circumstances in combination with the effects of covid restrictions and poor lab access.

The new researcher of UCLouvain started in April 2023, which led to a delay in experimental work due to a transfer of knowledge period.

5. Budget

a. Budget and realized costs

	Budget		Realization			
Partners	**costs**	**in kind**	**costs**	**TKI**	**cash**	**in kind**
UC Louvain	464.250	92.850	496.565	325.400	46.000	125.165
UTwente	146.875	29.375	231.818	72.500	45.000	114.318
Avebe	40.000	40.000	26.401	0	0	26.401
Corbion	40.000	40.000	7.500	0	0	7.500
Givaudan	40.000	40.000	10.810	0	0	10.810
ISPT	130.000	0	130.000	32.500	97.500	0
	861.125	**242.225**	**903.094**	**430.400**	**188.500**	**284.194**

b. Justifications for difference between initial budget and realized costs

Reallocation of the budget of 40Keuro for ‘unforeseen expenses’ which was included for hiring f.e.TNO for an update of their report on performance of the RMD (former project) by end of project. Both UCLouvain and UTwente, together with the project leader could provide for sufficient data to give a full report on the energy efficiency performance of the modified RMD dryer by the end of the project, and also to benchmark this with the former energy efficiency report of TNO (former ECN) for the RMD project in 2018.
Therefor of this budget of 40KEuro now 18Keuro was reallocated for prolongation of the hiring period of our expert project leader during the project prolongation, and for additional support by a master student at UCLouvain and any other additional supporting personnel with a maximum of 22Keuro.

Reallocation of the budget of 20KEuro for boarding an equipment builder was performed as the obtained results from spray drying tests were not sufficient yet to convince and board an equipment builder that had a good foundation to build on for a proper investment in building a pilot RMD dryer based on the current design rules for a better pilot. This budget of 20Keuro was therefor used for consumption of dry ice as a good medium to polish the inside walls of the vortex dryer after experiments, and for the extreme number of set-backs by broken-down auxiliary equipment.

Although the industry partners actively participated in the project by offering their technical spray drying expertise, providing valuable feedback and analyzing of powder quality, the industry partners have not been able to fully provide for their in-kind contribution of 40Keuro per industry partner as budgeted. This is due to the course of research set backs at UCLouvain. As intended the industry would participate in product quality confirmation of various model systems. The diversification of the model systems was planned for an overall positive effect on the research since specific product properties reveal details on the particle trajectories, the drying conditions encountered and the flow pattern in the dryer, as well as on the operating procedures, but it was not possible to execute this further investigation of model systems.

6. Results

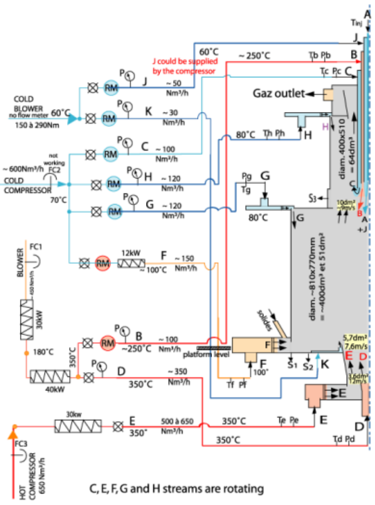
Results UTwente

A computational fluid dynamic (CFD) model based on the Lagrangian-Eulerian simulations with included Reaction Engineering Approach (REA) was used to investigate evaporation of the water from milk sprays. The model was applied to novel configuration of the spray dryer characterized by counterflow arrangement of the flows, high temperature central section and relatively cold temperature periphery, drying time of the product in the order of millisecond and immediate separation between gas and product flows. An overall good qualitative agreement between the model and observations done during the experiments was achieved.

Most of the CFD simulations were performed to optimize the performance of the experimental test rig and to find optimal process conditions. Based on the numerical simulations and experimental investigation of the feed viscosity and spray parameters, various modifications to the geometry of the dryer and process conditions were proposed. These modifications were related to the location of the solid outlets, diffusor configuration, spray parameters, feed flow, atomization pressure, feed preheating temperature, etc. All led to the improvement of the general performance of the test-rig. Also, based on the numerical simulations optimal process conditions for milk sprays were selected. Due to the focus on the improvement of the overall performance of the test rig, less attention was paid to the investigation of the other feed types.

Results UCLouvain:

Experimental condition



C, E, F, G and H streams are rotating

Courtesy: Axel de Broqueville

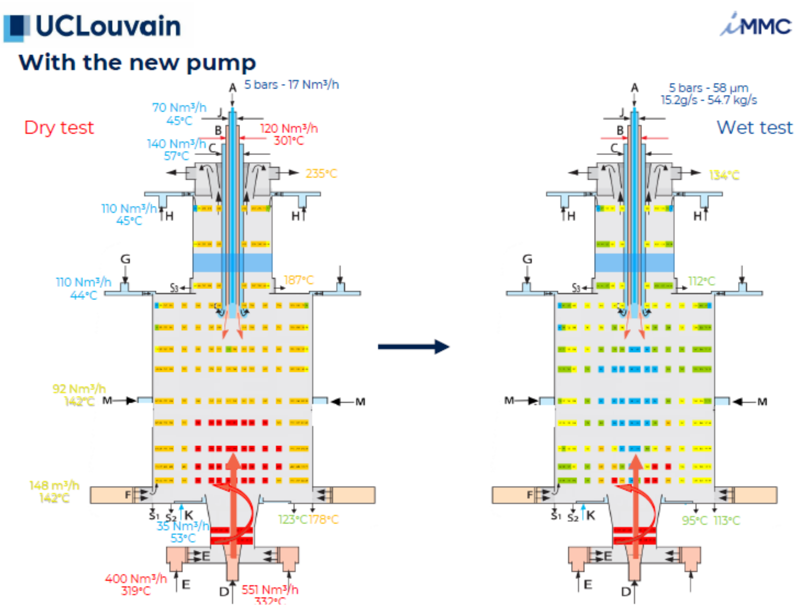
J:50 K:30 C:100 H:120 G:120 F:150
B:100 D:350 E:650 (Nm³/hr)

D and E line total temperature: 350° C
F cold line ~ 150° C

First dry test then wet test

Flow rates ~ 10g/s

Pressure A : 6 bar (Atomiser unit)
Pressure E: 850 mBar
Pressure D: 351 mBar



UCLouvain focused on carrying out experimental tests with the scaled-up set-up. In continuation of the previous project, initial tests were carried out with skimmilk to verify start-up and shut-down procedures and try increase the duration of the tests. Because of the large pilot plant scale of the equipment, it was experienced that unmounting, cleaning and remounting the set-up was difficult, even with the researcher being helped by technical staff. In order to support the researcher a dry-ice clean device was acquired to accelerate cleaning but was found expensive to use, which was not reported. In the last stage of the project a hot water Kärcher was acquired.

In line with the expectations of the project, a component of interest to the new industrial partners was quickly selected to continue the tests, i.e. maltodextrin. It has the advantage of being less sensitive to browning, is much more easy to dry than protein and lactose but also suffers from stickiness in a certain operating window.

The tests with maltodextrin allowed for trials to enter into a “steady state operation” , i.e. longer duration, opposed to evaluating start-up’s and shut down’s. The industrial partners pressed on this was of major importance to investigate technical teething issues as well as to arrive to a proper insight with respect to overall mass balance. The tests with maltodextrin were, however, hampered by a) more workload for the researcher who was clearly understaffed for this size of operation b) new findings with regards to degree of powder extraction and deposits c) various technical issues that required replacing equipment that was not budgeted:

(i) A brand new Boge compressor was acquired on own resources. It is used to supply pressure to the 4 atomizers in the chamber to allow for long-duration trials. Unfortunately, immediately the compressor had frequent automatic shut-downs. Boge accepted under guarantee to come on site and repair the compressor 4 times without resolving the issue. It was finally decided to replace the entire block of the compressor under guarantee. In the meantime, shorter duration trials could be carried out using a battery of compressed air bottles. The compressor issue, however, also discouraged the main (and experienced) researcher on the project who decided to leave the project, which was a major set back.

(ii) Various air heaters are used to heat up the hot air stream and the medium temperature air stream. Two of the heaters had to be repaired. One heater suffered damage after malfunctioning of a check valve by which water could enter the air feed lines causing short-circuiting of the heater. It became clear that this university design -on longer runs- was suffering from auxiliary component issues (having nothing to do with the vortex concept) leading to unfortunate and extensive downtime. In the meantime, only tests with reduced air heating capacity could be carried out.

(iii) Two air compressors are used to supply air to the hot air inlet and to the vortex chambers. One of the compressors suffered from overheating and could not be repaired. By lack of budget, the project coordinator managed to find a secondhand compressor relatively quickly. In the meantime, however, only trials with lower total air flow rate and, hence, capacity could be carried out. Furthermore, electrically connecting and getting into service the secondhand compressor proved to be more difficult than hoped and took another 2-6 weeks.

It is clear that this number of technical issues combined with the large pilot plant scale of the unit and the replacement of the experienced researcher on the project meant a serious set-back for the 2-year project from which we could not recover in time to finish all foreseen tests. Nevertheless, significant progress was made in operating the Radial Multi-zone Dryer:

(i) Asymmetry in the chamber: The counter-current injection of hot air and droplets can result in bypassing, which is detected by an asymmetry in the temperature profiles. Bypassing of hot air and droplets is to be avoided as it has a significantly negative impact on the drying and energy efficiency. Furthermore, because of the asymmetry, droplets are not sufficiently fast evaporated and pushed back away from the hot air inlet and are deposited in the hot air inlet area. The resulting fouling is problematic for long-duration operation and introduces a risk of fire of the deposited material. Such fire was indeed experienced and procedures to handle the situation optimized.

Several experimental tests were carried out along with CFD simulations at UTwente to identify possible origins of the asymmetry. The hot air is fed at the bottom of the chamber via a 90° tube bend, but then distributed within the hot air inlet. The hot air redistributor was redesigned based on the obtained data and installed into the set-up. This allowed to significantly improve the symmetry in the chamber, but some asymmetry remains and requires a further redesign of the chamber and in particular the hot air inlet.

(ii) Longer-duration trials: With the asymmetry improved and operating conditions optimized, maltodextrin tests of 10-80 minutes continuous powder production could be carried out. Longer duration trials deemed challenging because of variations of the liquid flow rate coming from the peristaltic pump (which again was a non-industrial solution) An external recycle loop on the pump was installed but could not fully eliminate the problem. A new continuous flow pump with mass flow measurement is needed.

(iii) Extraction, Particle Size and Temperature zones: Of major importance is proper particle size distribution – connecting to industrial needs, long term operation as well as powder extraction. In a new simplified design with industrial auxiliary components and proper safety interlocks these subjects require thorough attention. The vortex concept remains an elegant and innovative concept but the technical auxiliary teething problems require cooperation with an industrial equipment manufacturer to propel this concept to the next phase. Due to these teething issues, we could not arrive towards the temperature profiles, hot and cold leading to passing the glass transition quickly and catching particles in a cooler non sticky temperature zone, generating proper powder extraction.

The principal researcher on the project (Thomas Tourneur) is finishing his PhD thesis. Following chapters have been written and shared with the project coordinator:

- State of the art in spray drying and vortex chamber technology
- Axial multi-zone vortex chamber spray dryer
- Radial Multi-zone Dryer
- Sleeve for the protection of the spray nozzle
- Cylindrical extension of the Radial Multi-zone Dryer
- Scale-up of the Radial Multi-zone Dryer and addition of a cyclonic chamber.

The PhD thesis covers work from the previous and the Engender project. It will result in at least 2 publications in international peer-reviewed journals. One paper will report on the Radial Multi-zone Dryer design itself, including multiple nozzles and protective sleeve design, and the successful small pilot plant demonstration. The second paper will report on the scale-up of the technology to the large pilot plant, start-up and shut-down procedures, the influence of some important operating conditions, and design issues.

7. Discussion

a. Results

The operating principle is more energy efficient. The savings estimate seems realistic, though with scaling up risks. In this context, we see two major challenges: the complexity of the current design makes scale-up and stable operation in practice difficult. This has several reasons; the main one being the number of different airflows. Product quality remains a concern. In particular, the exposure of dry product to too hot air poses a risk here. This entails very high requirements for product/air separation. This ties in with the design question on the first point and places high demands on the droplet size distribution (when sprayed) and the particle size distribution of the resulting product. Technologies to control this are available but have to be incorporated in a new design.

b. Technical and organizational issues

There are still technical challenges to be resolved. During this complex project a lack of practical process- and product understanding was identified, which is not meant as criticism. A pilot drying system with trial capability may evolve to higher complexity than a run of the milk standard solution; as was witnessed in this case of fundamental research.

Furthermore, any drying system needs all kinds of additional auxiliary equipment. It is quite an achievement that UC Louvain went this far already with respect to this Research project.

However, due to these auxiliary equipment requirements and -as a result of 4 projects in a row- the current RMD set-up evolved to a “patchwork” design. A new -simplified- easy to inspect/clean design with functioning auxiliary equipment and adequate automation & logging will be necessary for the next development phase of this complex technology.

A major setback was created by the departure, at the end of 2022, of the PhD Student of UCLouvain who had been working on the 3 previous RMD projects and was very experienced with the technology and set-up. Recruiting and selection (including visa trajectory) led to a gap of 5 months in research activities, on top of this the logical timeline needed for the new researcher to get acquainted with the RMD, Research objectives, and the project consortium.

c. Lessons learned

Although the RMD concept is innovative it is clear to the consortium that a new design with input from an equipment builder/supplier is necessary as there are quite some standard solutions available. The scaled-up RMD was also build re-using pieces of the previous smaller RMDs and in particular partially re-using auxiliary equipment (e.g. two smaller compressors were available and used which delivered combined the required air flow rate – one single larger compressor would have reduced operational issues – same for the air heaters). The design of the core equipment must be simpler. For instance: wet-mixing / heating / weight in loss feeding / frequency inverters on blowers / compressors for pressurized airflows / dedicated pumps / pressure nozzle systems / process automation / safety interlocks / logging / etc etc all to name but a few standard items which would be highly supportive to any further research and trials.

A higher level of technical support will be necessary to achieve positive results in the coming months until mid April 2024. Two persons “on the floor” are generally required for trials at this scale as we have learned along the trial journey and this was not foreseen when submitting the project proposal. Modifications were not always communicated in sufficient detail by UCLouvain to UTwente, which led to greater discrepancies between CFD simulations and the actual running conditions of the RMD unit. This complicated dialogue with respect to CFD values and actual trial conditions. The low trial output of the first researcher (number of trials & repeat trials - when not confronted with mechanical issues) was a genuine point of frustration within the industrial partners.

8. Conclusions and recommendations

a. Findings

If continuation will take place in a new project, it is proposed to take operation “out of” the university environment. Our recommendation would be to use the knowledge currently available to create a simpler design. Start from scratch with the involvement of an equipment supplier.

Situate the installation either at a launching customer or at an Institute such as NIZO or similar.

Provide trials with sufficient process- and product technology support (more FTE in general).

Create a dedicated team with ample know how on spray dried products as well as spray rdying.

In **Appendix A** the calculations of UCLouvain and UTwente regarding energy efficiency are drawn up.

Main developments still required

- Find adequate design for the divergent feeding of the counter-current hot stream D, to prevent large droplets from penetrating too far in the hot bottom section, without generating too much dissymmetry.

- The new sleeve design is adequate, but it is necessary to improve the feeding of rotating cold gas in order to keep powder away from the sleeve outer cylindrical surface.

- Rotating fluidized bed must still be produced and its location should be checked. If possible, it should be split in 2 sections: one at the bottom of the vortex chamber and one in the middle.

Besides those three important items, streams optimization is still needed.

The conclusion of UTwente from experiments and CFD simulations and from experiments of UCLouvain is that the RMD is at least 20% more efficient than a conventional dryer.

b. Possibilities for further activities, research and/or spin off

A follow-up project is under investigation. Finding an equipment manufacturer that will be prepared to invest in building a prototype. An exploratory meeting was held was equipment builder Lübbers Anlagen und Umwelttechnik in September 2023. Although they are interested in participating in the development and design of a new vortex dryer as a small-scale enterprise, they lack finances to invest in multiple development projects and therefore will not participate in any follow-up activity.

9. Communication / dissemination

a. Activities

- Project page on ISPT website: https://ispt.eu/projects/eems/
  https://ispt.eu/projects/engender_compact-energy-efficient-dryer/

- LinkedIn:
  https://www.linkedin.com/posts/anne-van-der-zwaan_wur-utwente-stagglop-activity-6978790182099554306-8YmU/?trk=public_profile_like_view&originalSubdomain=nl

- During the annual NWGD Symposium this project as part of the ISPT Drying & Dewatering Program was brought to the attention of the NWGD drying expert community.
  ISPT Conference: https://ispt.eu/news/ispt-conference-2019-circularity-in-industry/

- Presentation of the project results during the ISPT Drying Program Day on 11 March 2024.

- News item on final results from project is planned for Q2-2024.

b. Public references

Publ.ID	**Year**	**Type**	**Submitted by**	**Reference**
PUB194	2022-June	Poster	Sriram Ramanathan	Poster Efficient spray dryer in a novel configuration of a milk dryer, by Sriram Ramanathan, Artur Pozarlik, for J.M. Burgers Centrum conference on 8-9 June 2022.
PUB240	2022-August	Abstract	Sriram Ramanathan	Abstract Efficient spray dryer in a novel configuration of a milk dryer, by Sriram Ramanathan, Artur Pozarlik, for NWGD Symposium on 22 September 2022
PUBxxx	July 2023	BSc thesis	J. Kleinhout, Sriram Ramanathan	J. Kleinhout, S. Ramanathan, A.K. Pozarlik, On the stabilization of impinging flows in the central region of the novel Multizone Vortex Dryer, 05.07.2023, BSc thesis, University of Twente.
PUB347	2023 Sept	Presentation	Sriram Ramanathan	Presentation Radial Multizone Dryer for Milk Drying for NWGD Symposium 21 September 2023
PUBxxx	2023 Sept	EngD Thesis	Sriram Ramanathan	EngD Thesis 'Towards optimization of Radial Multi-Zone Dryer', S. Ramanathan, supervisor G. Brem, A.K. Pozarlik

PUB	June 2024	Conf. proc.	Thomas Tourneur, Axel de Broqueville, Juray De Wilde	The Radial Multi-zone Dryer for efficient spray drying: Concept and experimental studies on a small and large pilot scale unit
PUB	Aug 2024	Peer-reviewed journal	Thomas Tourneur, Axel de Broqueville, Juray De Wilde	The Radial Multi-zone Dryer for efficient spray drying: Concept and experimental studies on a small pilot scale unit
PUB	Nov 2024	Conf. proc.	Thomas Tourneur, Axel de Broqueville, Juray De Wilde	Efficient spray drying using a novel Radial Multi-zone Dryer
PUB	Dec 2024	PhD thesis	Thomas Tourneur	Radial Multi-zone Dryer for Efficient Spray Drying: Theoretical and experimental study
PUB	Dec 2024	Peer-reviewed journal	Thomas Tourneur, Santanu Dey, Axel de Broqueville, Juray De Wilde	Experience with scale-up of the Radial Multi-zone Dryer for efficient spray drying

10. Acknowledgement

This project is co-funded with subsidy from the Topsector Energy by the Ministry of Economic Affairs and Climate Policy.

Appendix A – Calculations regarding Energy Efficiency

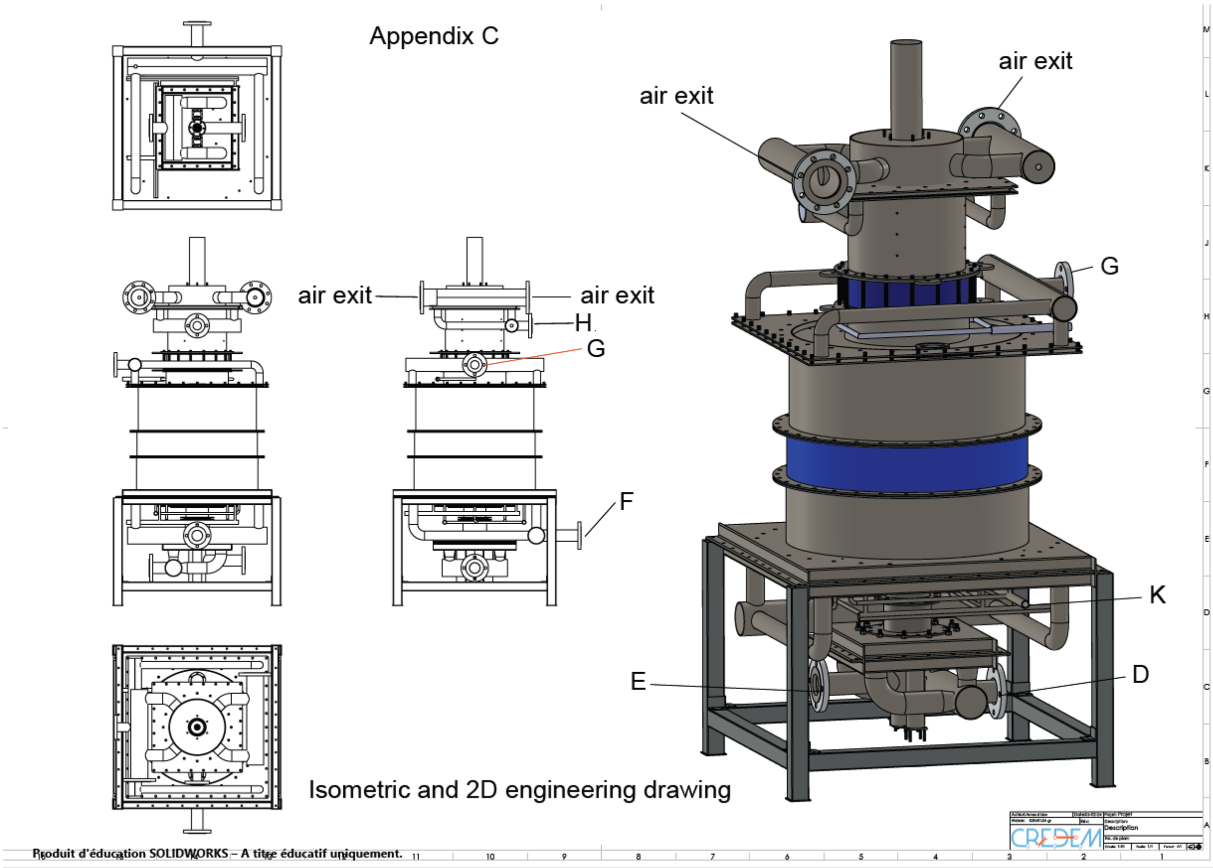
Calculations UCLouvain regarding Energy Efficiency

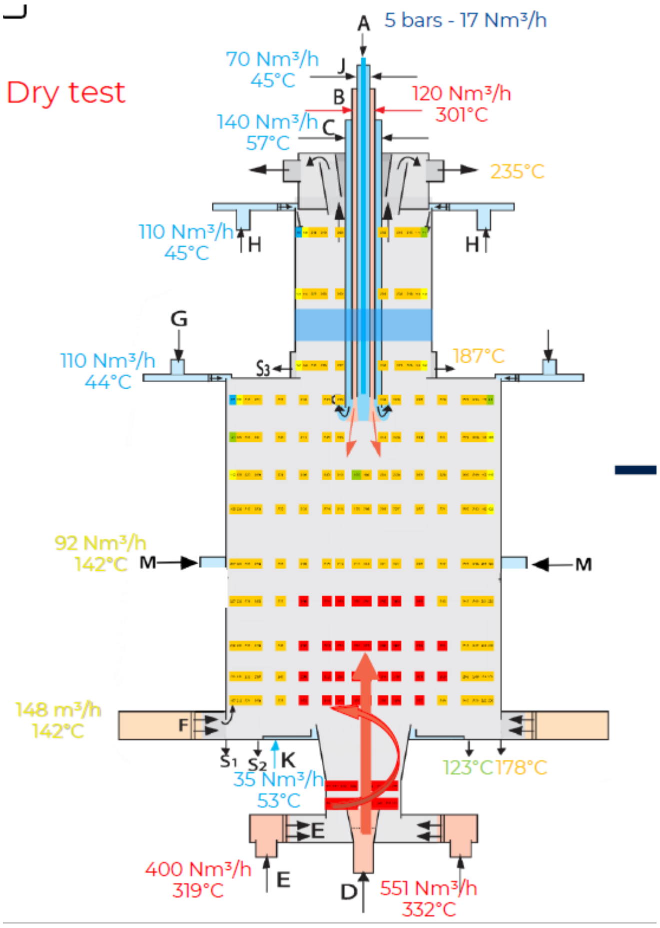
R800 Real Heat Efficiency

Heat efficiency is directly proportional to the cooling capacity of a droplet cloud crossed by hot gas. In theory a dense droplets cloud can cool the gas to less than 100°C, provided that it is wide enough and contains a large enough number of small enough droplets.

R800 is designed for feeding:

- in the central zone, about 1,500 kg/h hot air, (streams B, D and E), at about 350°C;
- along the periphery and the sleeve outer surface, about 1,300 kg/h air, split in
    - a warm stream F at about 130°C, designed for crossing a dense rotating fluidized bed of milk powder. Mass flow rate should be high enough (about 600kg/h) for finishing the powder drying.
    - a cold stream, C, G, H and K, at room temperature, (heated by the compressor, in our case).





Evaporation capacity
A temperature reduction of 1°C of 1kg air produces 0.25 Calories. It takes 550 Calories for evaporating 1kg water.

Warm stream F: 600kg/h at 130°C (Air is heated from 20°C to 130°C)

Warm dry air crossing a dense humid rotating fluidized bed can be cooled to relatively low temperature (close to the dew point). In practice, an 80° temperature drop, giving an efficiency of 80/110=72.7% is realistic, with dense bed. Evaporation capacity is about:

600kg/h*80°C*0,25 Cal/kg/°C/550Cal*kg steam = 22kg/h steam.

It must be noted that the ability to obtain a dense fluidized bed must still be tested.

Hot stream B, D and E: 1,500kg/h at 350°C (Air is heated from 20°C to 350°C)

It is assumed that only 50% of the heat capacity (corresponding to a 165°C temperature drop) is used by the droplets cloud in the R800 pilot due to its small size (too short residence time and dissymmetry). it gives an evaporation capacity of:

1,500kg/h*165°C*0.25Cal/kg/°C/550Cal*kg steam = 112 kg/h steam

Cold stream C, G, J and H: at least 700 kg /h at room temperature

It is needed for maintaining a relatively dry (<45gr water/kg air) and cold (< 100°C) air layer along the periphery and the sleeve in order to prevent powder stickiness. It is also needed for generating proper centrifugal force in order to accumulate powder along the periphery. Optimum operating conditions should minimize its needed quantity. It is not necessary to heat that stream.

Spray nozzles
In order to produce a dense cloud of small droplets, multiple narrow cone spray nozzles, (preferably full cone) of small droplets are needed. In a pilot unit 2 fluid nozzles are preferred for their capability to produce very narrow full cone of very small droplets.

In a large-scale industrial plant, 2 fluid nozzles are not required. Longer residence time should allow better heat recovery (a 30% improvement, corresponding to 65% efficiency) for producing 30% more milk powder and larger droplets should allow better powder recovery.

Total heat needed

1,500kg/h*(350°-20°) *0.25Cal/kg/°C + 600kg/h*(130°-20°) * 0.25Cal/kg/°C = 140 kCal/h.

Total heat used: 132kg/h steam * 550 Cal/kg = 72,6 kCal/h

Efficiency: 72,6/140 = ~ 52%. This could be increased to more than 65% in a large-scale industrial unit.

In summary:

A 2,800kg/h total air stream in a 0.45 m³ pilot plant is expected to vaporize 132 kg/h water contained in 220 kg/h milk at 40% concentration, in order to produce 88 kg/h milk powder. Production capacity could be increased by 30% with the same heat and air quantity in a large-scale industrial plant.

It requires 140 kCal/h to increase average air temperature by about 200°C.

The average outlet gas temperature drop is about 100°C. (This is our goal). During testing, 85°C temperature drop has been reached so far.

Average water content in hot gas outlet is about 48 gr water/kg air (60gr/kg for an industrial plant), but it should be split in a small outlet stream (about 300kg/h) at a much lower temperature and much lower water content for powder recovery and the main gas outlet at more than 120°C and higher water content.

Preheating of the air with hot outlet gas could improve the energy efficiency. Alternatively, hot outlet gas could be partly recycled, because humidity level is less significant in a hot gas (> 100°C), provided that it is powder free.

Heat losses are neglected because of relatively small size plant.

Air blower energy should be added.

Main developments still required

- Find adequate design for the divergent feeding the counter-current hot stream D, in order to prevent large droplets from penetrating too far in the hot bottom section, without generating too much dissymmetry.

- The new sleeve design is adequate, but it is necessary to further improve the feeding of rotating cold gas in order to keep powder away from the sleeve outer cylindrical surface.

- Rotating fluidized bed must still be produced and its location should be checked. It is possible that it will be necessary to split it in 2 sections: one at the bottom of the vortex chamber and one in the middle.

Besides those three important items, streams optimization is still needed.

Calculations and Findings UTwente regarding energy efficiency

Energy comparison

From the table: 7.3, the evaporation rate of the water is known.

Solid Outlets	**Mass Extracted[%]**	**Avg Temp [◦ C]**	**Avg dia [μm]**
S1	41.2	46.6	31.2
S11	23.1	48.9	30.2
S2	20.9	48.8	28.1
S3	11.6	65.4	24.6
Gas Outlet	11.6	78.8	12.5

Table 7.3: Extraction data for mass flow rate 165.6[Kg/hr] with S11 outlet

In the particular simulation, the mass flow rate of the feedstock was kept at 0.046[Kg/s] with 40% solid content. The total extraction was 108.4% indicating that there is 8.4% of water in the extracted powder.

The total enthalpy of the central drying air, which is from the ”d” and ”e” inlets;

$Q_{d,e} = [m_d + m_e][C_p][\Delta t]$

$= [0.102 + 0.11][1][330 - 25]$

$Q_{d,e} = 64.66[KW]$

(F.1)

The air from the tangential inlets is also relatively at high temperatures which aids in evaporation. The total energy from the cyclonic inlets (”g”, ”h”, ”m”, ”f”) is as follows;

$Q_g + Q_h + Q_m + Q_f = 5.065[KW]$ (F.2)

The total mass flow rate of water in the feedstock solution is 99.36[Kg/hr], the 8.4% accounts upto to 5.56[Kg/hr]. Therefore total water evaporation rate is 93.86[Kg/hr].

$93.86[Kg/hr] \equiv 69.725[kW]$

$1[Kg/hr] \equiv 0.743[KW]$

(F.3)

In a conventional multi-stage dryer (comparison is done with a multistage dryer as the RMD, in theory, is a multi-stage dryer), 1.2kg of steam is required to evaporate 1kg of water.

1.2kg of steam at 22[bar] (as per the conventional MSD/FSD/Filtermat) At 22[bar], the saturation temperature of the steam is 218.452[◦C]. Assuming that the steam entering the dryer is pure vapor, the enthalpy $h_g = 2800[KJ/Kg]$. Therefore the total energy is $m_{steam} * h_g = 1.2 * 2800 = 3360[KW]$ (F.4)

$1[kg/hr] \equiv 3360[KW]$ (F.5)

ESC efficiency is given by ESCefficiency = ESC

Lwater

(F.6)

Lwater is the latent heat of vaporization of water 2337.46 KJ/Kg and the ESC is the energy-specific consumption, that is energy required by the reactor to evaporate 1 kg of water. In the case of RMD the heat input to evaporate 1 Kg/s of water is 2676.13 [KW], therefore the ESC efficiency is 1.14.Similarly in conventional multistage dryers, the ESC efficiency is 1.44.

Conclusion is that the RMD is 20.8% more efficient than the conventional dryer.