ENERGY EFFICIENT INTENSIFIED SPRAY DRYING

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Abstract

A CFD code for the prediction of the flow in a spray dryer has been developed as a design tool for optimisation of spray drying plant efficiency. The advanced research CFD code, that takes into account buoyancy effects due to evaporation and product specific drying characteristics was developed by the National Technical University of Athens within the scope of this project supported by contributions of Bayer and Niro. It incorporates a collision / coalescence developed by Cranfield University and an evaporation model. The code was evaluated against experimental measurements carried out by Imperial College, Bayer and Niro and commercial CFD codes, used by Bayer and Niro. A Heat Damage Index Number was defined by the National Technical University of Athens, Imperial College, Bayer and Niro and incorporated in the advanced research CFD code, allowing a prediction of dryer performance in terms of product quality to be established as an output of the code. This number indicates the length of time a particle has resided in an environment of a specific critical temperature or higher.

The experiments carried out by Imperial College include a study of the effect of airflow bulk velocity, temperature and turbulence levels on the evaporation rate of droplets, a study of the development of co-axially constrained turbulent jets. Finally Imperial College carried out simultaneous size and velocity measurements of partially dried particles of arbitrary shape by shadow Doppler velocimetry in both laboratory and industrial scale dryers. The preparation and taking of the measuring in industrial scale dryers were performed in close co-operation of Bayer, Imperial College and Niro at the industrial partner’s site. The shadow Doppler velocimeter instrumentation was modified by use of fibre optics to allow the use of a protective optical probe for the measurements at industrial scale. The shadow Doppler velocimeter's accuracy was calculated by the generalised Lorenz-Mie Theory by the University of Rouen.

Finally a parametric study was carried out on several designs by the National Technical University of Athens, Bayer and Niro to establish new designs of spray dryer geometry with higher energy efficiency while maintaining product quality. All the results of the project became a part of the new computer based design methodology for spray dryers with increased thermal efficiency, which was developed throughout the project.

1. Partnership

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2. Objectives

The objective of the project was to develop state-of-the-art CFD-based design methodology for the optimisation in terms of energy efficiency of spray drying plants. This design methodology enables the optimisation of spray dryers in terms of more compact (intensified) plant, greater energy efficiency and higher product yield while maintaining product quality. The project results will assist the spray dryer designer to control the drying gas flow pattern, the droplet/particle flight paths and the heat and mass transfer process so as to prevent product charring, coating of the chamber walls and of hot surfaces in the drying air inlet region, as well as enhance or prevent agglomeration. These process characteristics must be considered according to the demands of each product.

The difficulty in improving energy use or intensifying the unit operation of spray drying was the multiple parameters at a designer’s disposal. The flow pattern is complicated and the understanding of underlying processes, such as agglomeration, was poor: Thus empirical developments were unlikely to lead to satisfactory process intensification. It was also an objective of this project to increase the energy efficiency of spray dryers and to intensify the design of this unit operation, primarily through the use of a design tool in the form of a computational fluid dynamics (CFD) computer code. The code incorporates a novel model of particle agglomeration and a model of the characteristic-drying behaviour. It has been evaluated by means of measurements at laboratory and industrial scale. To fulfil the aims, the objectives and expected technical achievements of this work were to:

- develop a laser-based instrument, the shadow Doppler velocimeter (SDV), which permits the simultaneous measurement of the size and velocity of spherical as well as non-spherical particles as found in spray dryers.
- calculate the accuracy of the SDV instrument through computer codes, which describe the scattering of laser light.
- measure, by optical instrumentation, evaporation rates of particles in turbulent flows under carefully controlled conditions permitting precise evaluation of the accuracy of CFD predictions of evaporation rate in spray dryers.
- measure spray size and velocity distributions within a laboratory-scale model of a spray dryer using optical instrumentation and also measure the field distribution of a scalar variable analogous to temperature or humidity.
- measure particle size, velocity and flux in industrial scale spray drying plants at industrial installations using the SDV instrument.
- develop a new model for agglomeration of particles suitable for use in the description of a spray dryer and incorporate this model in partner NTUA’s CFD code.
- assess the accuracy of a commercial and of the NTUA CFD codes by comparing predictions with the measurements at laboratory and at industrial scale.
- use the advanced research, and the evaluated commercial, CFD codes to assess the effectiveness of proposed new and retrofit designs of spray dryers in terms of improved process intensification, improved energy efficiency while maintaining product quality.

3. Technical description

3.1 Task 1 - Theoretical evaluation of a shadow Doppler velocimeter

The University of Rouen undertook the calculations of the accuracy of the SDV instrument. The geometry studied is representative of the actual device developed at Imperial College. However, a unique thin lens was used instead of a complex three-lens arrangement. Nevertheless, this thin lens was chosen to be equivalent to the three-lens arrangement of Imperial College. The angle between the two incident beams was equal to 2.86°, and the incident wavelength was 0.488 µm. The lens L1 had a focal length equal to 600 mm and a diameter equal to 100 mm. This lens was located at 720 mm from the intersection of the two incident beams. The image plane was located 3.6 m behind the lens, with a resulting image magnification of 5.

The computational scheme used in this study is fairly standard. It was based on the Generalised Lorenz-Mie Theory (GLMT), associated with the localised approximation to compute the scattered field’s incident on the input surface of the lens. The thin lens transform was used to compute the fields from the input surface to the output surface of the lens, and a Huygens-Fresnel quadrature allowed one to compute the fields from the output surface of the lens to the detector plane. To numerically compute the Huygens-Fresnel quadrature, a Hopkins scheme was used. The detector plane could be arbitrarily located on the axis, including the case of it coinciding with the image plane. The detector plane was understood as being located at the image plane as predicted from the nominal focal length (here 600 mm). The detector is assumed to be a line of 640 regularly spaced points. This scheme of computation had already been used for on-axis imaging under one plane wave or one Gaussian beam illuminations and for in focus off-axis imaging with one Gaussian beam.

The same code was used for all the cases. Input parameters were changed to match the cases examined. In particular, the phrase "plane wave" is used to designate a Gaussian beam with a diameter equal to 3 mm, i.e. much larger than the biggest particles under study (80 µm in diameter) and the phrase "Gaussian beams" is used to designate a Gaussian beam with a beam waist diameter equal to 300 µm.

3.2 Task 2 - Measurements by SDV of dispersed phase and scalar field in a lab scale spray dryer

In order to understand the mixing process within a spray dryer during its operation it was necessary to investigate the temperature gradients, humidity variations, evaporation rates, velocity, droplet size and residence time distribution, obtaining appropriate data wherever possible. Although there are measurements of the aforementioned quantities published separately and for a wealth of flow geometries, there is no single comprehensive study of all quantities for a particular dryer geometry. Thus it was necessary for the purposes of this project to obtain the most comprehensive set of data possible.

3.2.1 Evaporation measurements

The evaporation rates of droplets in a heated airflow as a function of turbulence level, airflow temperature and velocity were measured at Imperial College. The task was completed by collecting data on the evaporation rate of droplets in a heated airflow and its dependence on the airflow temperature and velocity. The evaporation rate is estimated by measuring the size of a droplet at several positions along its path as it is accelerated by a heated airflow. The experiment is then repeated at different temperatures and turbulence levels to establish their effect on the evaporation rate. The experimental apparatus used for the measurements of the evaporation rate of monodisperse droplets consisted of a "Phase Doppler Anemometer" optical arrangement, a custom built air-heating unit, a monodisperse droplet generator and a Perspex cylindrical duct for optical access with the PDA.

3.2.2 Passive scalar field measurements

The task was completed by constructing a small lab-scale, isothermal, single-phase spray dryer, and measuring the distribution of the Mixture Fraction of injected Argon in the measuring volume as well as and by performing experimental simulation of the process. The Mixture Fraction of Argon acts as a passive scalar, which is a partial analogue for temperature or water vapour. The distribution of Mixture Fraction of Argon in this simplified spray dryer simulation provides the partners with data for evaluation of their CFD codes. The small lab-scale, isothermal, single-phase spray dryer simulation set-up was based on the injection of a jet of an Air and Argon mixture into a co-axial surrounding airstream chosen based on the Craya-Curtet similarity of jets theory. The diameter of the cylindrical ducting for the secondary flow was chosen for convenience and material availability. The secondary airflow was set by Reynolds down-scaling of the test dryer at the Bayer site in Leverkusen. The ducting consisted of several flanged sections of 80, 90, 180 and 270 millimetres length allowing a piece of ducting designed for optical and physical access to be positioned at a variety of distances from the injection point. This physical access allowed measurements on samples from the flow to be taken, in order to establish the local concentration of Argon. This local concentration was measured using a Katharometer.

The secondary flow was arranged to have a flat profile at the point of injection. This was achieved by placing two constraints in the flow upstream of the injection point, thus causing large pressure drops. These pressure drops caused the flow to emerge with uniform velocity across the duct cross-section. The constraints were both baffle plates with 5 mm holes arranged radially, with a pitch of 1.5 mm to give an open area ratio of 0.5. The plate closest to the point of injection also acted as a turbulence generator. The length-scale of the turbulence is thus arranged to be about 5mm. The velocity profile was found to be axi-symmetric and the velocity was uniform over a large part of the cross section.

3.2.3 Simultaneous sizing and velocity measurements by SDV

The task was completed by collecting data on the size and velocity of droplets in a heated airflow. The experiments were carried out using Shadow Doppler Velocimetry (SDV). The collision and coalescence of droplets is also examined by comparing the probability density function of droplet size compared to that immediately below the nozzle. The experimental apparatus consisted of a "Shadow Doppler" optical arrangement, a commercial air-heating unit, a Delavan two fluid nozzle and the laboratory spray dryer assembly.

In order to provide the most accurate and complete boundary conditions possible for the evaluation of the CFD codes, the spray produced by the Delavan nozzle was characterised by use of SDV. This characterisation comprised of measuring the size distributions and velocities of the droplets produced by the nozzle under the operating conditions to be used in the lab-scale spray dryer. Sprays of water and 33.3% by mass Maltodextrine solution were characterised at a vertical distance of 25mm from the nozzle.

3.3 Task 3 - Develop and Use shadow Doppler velocimetry within industrial spray drying units

Shadow Doppler velocimetry is an optical technique for the simultaneous sizing and velocity measurements of arbitrary shaped particles first proposed by Hardalupas et al. (1994). It is differentiated from other optical sizing techniques by its independence from the amplitude of diffractively – scattered light. The method is based on the collection of light diffracted by a particle illuminated by two laser beams. Particle sizing is achieved by directly measuring the image (shadow) produced by diffraction. Since the technique is not amplitude based, no complex calibration of the developed instrument is required before measurements. The technique is ideal for use in flows to which access is gained through optical windows. The strictly geometrical definition of the sampling space area results in particle mass flux measurements of higher accuracy than those of intensity-based sizing techniques. Sizing errors should not exceed 8% for the mean and 10% for the RMS values and the accuracy of the Cartesian velocity measurements should be better than 10% in the mean and 15% in the RMS. The technique was modified with fibre-optic technology to allow measurements in hot, humid environments with high particle density, by use of a probe.

A probe was required to cool the instrument, maintain the optical surfaces clean and without condensation. It was decided, in order to minimise the probe size that all electronic components should remain outside the plant, while the necessary optical components were placed inside the probe. Due to limited access to the drying tower, the probe would need to be cantilevered inside the tower from one side of it. The optics behaviour and resulting misalignment inside the probe as the dryer temperature increased was a cause for concern and it was decided not to use mirrors inside the probe. Fibre optic cables were chosen to transmit the laser light to the far side of the probe, where a transmitting unit was placed, and the receiving optics were placed near the dryer wall. The linear diode array and photomultiplier remained outside the probe limiting the optical components inside the probe to lenses and fibres. In the spray drying tower environment, the high number of particles crossing the beams along their length (outside the probe volume) causes the signal from the linear photodiode array to be very noisy as well as significantly reducing the intensity of the laser beams, due to light scattering. For this reason two lengths of aluminium box section were mounted on either side of the probe volume, maintaining the flow disturbance to a minimum while protecting the beams from particles in the flow and thus improving the acquired signal.

3.4 Task 4 - Development of a computational model for use in the NTUA CFD code

3.4.1 Collision and coalescence model

The first step in developing the collision model was to define when a collision occurs. Since only a single particle was being tracked, it was not possible to calculate the occurrence of a collision directly. In order to specify this collision time the idea of a Mean Free Path (MFP) length from the study of particle kinetics was used. This allowed us to specify the time between successive collisions and the distance travelled by the tracked particle between collisions. Due to the presence of concentration gradient within the flow it was necessary to continuously update this MFP length as the tracked particle travelled through the flow field. This distance could be converted to a 'mean free time' that corresponds to the time between collisions.

The second part of the process was the collision model. Clearly for the case of binary collisions it was necessary to specify a collision partner for the tracked particle. A virtual particle was therefore created for the purposes of the collision. This new particle was termed the 'shot' particle and the particle being tracked as the 'target' particle. The shot particle corresponded to a particle selected out of the particle cloud found at the current location and any change in mass, momentum or kinetic energy that occurred due to the collision was taken into account in the second phase statistics. The properties of the shot particle were chosen at random from given distributions. Its size was taken from a Rosin-Rammler distribution with specified mean and exponent parameter. At the collision time the virtual 'shot' droplet with a random velocity vector and random contact point was introduced.

Next, it was necessary to distinguish between coalescing and non-coalescing collisions. Whether two colliding droplets would coalesce or not was an extremely complex issue and depended on a large number of factors such as droplet Weber number, the collision incidence angle and the physical properties of the droplets or particles. Since at the time little data was available for these values in spray dryer flow conditions, coalescence probability was specified as an input to the model.

A random number $(0 \le \varepsilon \le 1)$ was generated and compared against the specified coalescence probability, ε_c. If ε was greater than ε_c then an inelastic non-coalescing collision was said to have occurred and the target droplet velocity after collision was calculated. If $\varepsilon \le \varepsilon_c$ then a coalescing collision occurred and the target droplet mass is simply specified as the sum of the two colliding masses and again the velocity after collision is calculated. After a collision the MFP was recalculated and the process repeated until the droplet had left the calculation domain.

3.4.2 Evaporation model

The evaporation of droplets in a spray involves a simultaneous heat and mass transfer process in which the heat for evaporation is transferred to the droplet surface by conduction and convection from the surrounding hot gas and vapour is transferred by convection and diffusion back into the gas stream. The analysis used for this study was based on the work of Lefebvre. First the hypothetical case was considered where a liquid droplet is instantly injected into a gas at elevated temperature. At typical injection temperatures, the liquid vapour concentration at the droplet surface is low, and there is little mass transfer (diffusion) from the droplet early in the process. In general, temperatures are not uniform within the droplet, with the maximum temperature located at the surface due to the finite heat conductivity of the liquid. As the liquid temperature rises, the rate of mass transfer increases as a result of higher vapour concentration at the droplet surface. This has two effects; an increasing portion of the energy reaching the droplet surface must supply the heat of vaporisation of the evaporating liquid, and the outward flow of liquid vapour in the boundary layer reduces the rate of heat transfer to the droplet. This slows the rate of the increase of the liquid surface temperature and later on in the process, droplet temperatures become more uniform. Eventually, a stage is reached where all the heat reaching the surface is utilised for the heat of vaporisation and the droplet stabilises at the wet-bulb temperature. The effect of convection on the rate of heat transfer and evaporation is also considered.

The next level of complexity was to account for the time taken for the droplet to achieve the wet-bulb temperature. The *infinite conductivity* model considers a droplet with rapid internal mixing where droplet temperature is spatially uniform but varying with time. The uniform droplet temperature arises by letting the liquid thermal conductivity go to infinity. The temperature, T_s of the droplet varies with time. When the droplet reaches its *wet-bulb* condition, the heat and mass transfer number are equivalent and its temperature remains constant and the evaporation continues at a constant rate, as given by the d^2 *law model*. During the heat-up period, however the droplet diameter varies with time.

A further development to the model considered variations of composition and temperature within the droplet in both time and space. It was assumed that internal liquid motion was not significant, and heat transfer inside the droplet was controlled by thermal diffusion only, hence the model was called the *conduction limit* evaporation model. The surface temperature was still assumed to be uniform. The level of detail presented by the *infinite conductivity* model was suitable for the flows that are of interest to us, and hence the added computational expense of the *effective conductivity* model was not warranted for this project.

3.5 Task 5 - Compare predictions of dryer performance between NTUA and commercial CFD codes

In order to provide a sufficient tool to develop guidelines for new and improved spray dryers the NTUA CFD-code has been extended and adapted to the specific requirements of predicting the spray drying process. Models have been included for heat transfer, evaporation and coalescence while local grid refinement is used for a better resolution of the near nozzle region. The effects of density gradients in the flow were also taken into account through buoyancy terms in the momentum equations and it was found that they have an important influence on the flow field. The code has been validated against measurements published in the literature and calculations of the particulate and gas phase aerodynamics in an industrial scale spray dryer have been performed. Preliminary comparisons with the calculations performed by BAYER using a commercial CFD code have shown general agreement.

Numerical calculation of the scalar mixing, which was experimentally studied in a laboratory scale apparatus at IMPCOL, was performed. Calculations were performed by NTUA using their universal CFD-codes and by BAYER using commercial CFD-code. The results of the calculations were compared, shortcomings analysed and the codes and the guidelines for setting up a problem in the CFD-codes improved.

In an initial step to access the CFD-codes of NTUA and BAYER an industrial scale spray dryer was chosen. The pilot plant industrial scale spray dryer geometry provided by BAYER as well as boundary and operating conditions were agreed upon.

To compare the advanced research CFD-code of NTUA and the commercial CFD-code used by BAYER the injection of the feed stock in the spray dryer was modelled as a cone injection. Water was chosen instead of a feed stock suspension for the comparison. It was much easier to model only the evaporation without including the complex modelling of the drying of a suspension droplet. In order to get realistic inlet conditions the spray of a Delavan hollow cone nozzle was measured and this data were compressed into six different size classes of droplets. Each class was specified by its one velocity magnitude, velocity direction, droplet size and mass flow. The total of the six cones resulted in a spray equivalent to the measured hollow cone spray.

3.6 Task 6 - Design of new spray dryer arrangements, using CFD codes, and assessment in terms of energy efficiency and process intensification

The CFD tool gives the chance to study not only a well known design of a spray tower but also new, unconventional, innovative and creative forms. Since the goal of spray drying is to get a dry product, the design of the study showing the highest mass fraction of water in the exhaust is the best in terms of energy efficiency. This study will not give a final design for the most efficient spray dryer. However, it demonstrates the power of this tool as well as the necessity to look for and to study innovative design forms.

To evaluate the efficiency of the different spray dryer designs one needs a tool to compare the different results. Index numbers chosen carefully are an outstanding tool to work out this crucial question.
In terms of energy efficiency equation 3.6.1 is frequently used:

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_{sur}} \qquad (3.6.1)$$

What has to be taken into account, is that one can only apply this equation in order to compare different types of spray dryer designs if the product which is dried in the spray dryer leaves the apparatus having exactly the same residual moisture content. And this is in general not the case. This point is very important since the water leaving the apparatus not as vapour but as liquid has a tremendous influence on the energy balance. Furthermore equation 3.6.1 is only valid in the case of an adiabatic dryer.

4. Results and conclusion

4.1 Bayer AG, Niro A/S

The SDV has the ability to measure spherical as well as non-spherical particles down to particle diameter of about 5 µm and 10 µm, respectively. The SDV is in principle suitable to measure particle size and particle velocity in an industrial scale spray tower and with some improvements of the measuring device will extend the measuring range of the device and make easier its operation. The advanced research code of NTUA model improves the meaningfulness of the CFD-calculation. The “Heat Damage Index Number” (HDIN) is an extraordinary tool to assess new spray tower designs in terms of product quality and energy intensity. Measurements of the scalar field were performed and used to evaluate and improve the advanced research and commercial CFD-codes. Of great importance is the round jet anomaly to correct calculations of the scalar field in the case of a two dimensional problem. In order to calculate the evaporation during a spray drying process, it is necessary to set up a model of the evaporation and incorporate it in the CFD-code. Furthermore the buoyancy effect has to be taken into account. Design guidelines were developed on the base of the CFD-calculation using the improved CFD-codes and the experience of partners NIRO and BAYER. Of great value for energy efficient intensified spray drying is the use of meaningful index numbers. Numbers known from literature were used, like energy efficiency, and new numbers were developed like the Heat Damage Index Number (HDIN). This number gives outstanding information on the intensity of the process as well as on the product quality.

4.2 University of Rouen

Table 1 summarises the conclusions. When the scatterer diameter is larger than about 40 µm, measurements for sphere or cylinder are equal, and in good agreement with the actual diameter. For a scatterer diameter of 10 or 20 µm, the measure overestimates the diameter of the sphere and cylinder. This over estimation increases when the scatterer diameter decreases. Furthermore, this overestimation is always larger for a cylinder than for a sphere.

Real Diameter	10 µm	20 µm	40 µm
D measured (cylinder)	24 µm	28 µm	40 µm
D measured (sphere)	14 µm	24 µm	40 µm
$D_{cylinder}/D_{sphere}$	1.7	1.2	1

Table 1 Comparison between the measured particle size

4.3 Imperial College of Science Technology and Medicine

4.3.1 Data on the variation in droplet evaporation rate in a turbulent, heated airflow

The Probability Density Function (PDF) of the measurements indicated that collisions resulting in droplet coalescence took place within the 450 mm through which measurements were taken. In order to obtain data on the evaporation rates of the droplets under the various tested conditions, the sizing and velocity data of the non-colliding droplets was used. The evaporation rates were found to increase with the velocity and temperature of the surrounding airflow. Moreover, the turbulence grid also increased the evaporation rate while also increasing the percentage of colliding droplets. The initial velocity of the droplets at the injection point was 9 m/s. The droplets were very rapidly accelerated in the airflow to the airflow velocity and then continued accelerating under gravity.

4.3.2 Laboratory-scale measurements of passive scalar field and simultaneous droplet size and velocity

According to the Craya-Curtet number Ct=1.1 used in this experiment, no recirculation zone was formed as the jet expands. Changing the Craya-Curtet number of the flow, adding shoulder to the flow entry, adding a bluff body around the nozzle and modifying the turbulent length-scale of the flow, allowed data to be obtained in a similar fashion according to the partners needs.

4.3.3 Simultaneous sizing and velocity measurements by SDV in a lab-scale spray dryer

The results showed a highly turbulent flow with large recirculation zones in the laboratory scale spray dryer. The droplet size distribution, even 60 mm from the nozzle shows very fine droplets compared to the nozzle spray size distribution above. This indicates a large degree of evaporation took place in the first moments of contact between air and spray.

4.3.4 Simultaneous measurements of particle size and velocity in a pilot plant spray dryer

Flow characteristics analysed included the particle size, axial and circumferencial particle velocity, and the particle trajectory angle. The effect of the drying medium inlet temperature, nozzle operating pressure and radial position were examined. For the purposes of detecting differences in particle path characteristics, particles were grouped into 60-70, 100-150 and 170-200 micron series.

The validation rate (ratio of particles with accepted size and velocity measurement to the total number of particles detected in the probe volume) was almost constant during each measurement batch with some deterioration (~1-2%) with time due to misalignments from heating of the optics and mechanical vibrations.

Although it was evident there was significant fluctuation with time; it was not possible, due to the low number of measurements and validation rate to detect any periodicity in the flow. The nature of the technique means that measurements were not acquired at fixed intervals, which did not allow the use of a normal fast-Fourier-transform (FFT) technique to establish a dominant frequency. A USFFT (unequal spacing fast-Fourier-transform) technique was therefore applied to the data. This resulted in a period of 25-40 s being detected in some of the flow characteristics. Since the periodicity was only pronounced in measurement positions with large numbers of measurements, it was not possible to detect a trend in the frequency of this periodicity with changing flow characteristics.

4.4 Cranfield University

The inclusion of an evaporating droplet model into a collision model produced results, which enable the study of a number of more complex flow characteristics. The current calculation is based on the droplet free-falling in a stagnant gas. The collision model uses a mean free path time between collisions and, during this time, the droplet is allowed to evaporate. Thus the droplet diameter reduces between collisions and when a coalescing collision occurs, the droplet diameter increases.

The results show an initial increase in droplet diameter before the evaporation process becomes dominant and the droplet is vaporised fully. It was assumed that at each collision the droplet coalesces with a virtual shot particle. The evaporation of the droplet can be seen between collisions. The mean free path, and hence time between collisions, increases as the droplet size decreases, reflecting the fact that a smaller droplet is less likely to encounter another droplet.

The effect of mass loading was also investigated using inlet loadings of between 2% and 40%. In the case of the lowest value very little collision is observed and only a small increase in the concentration for size groups larger than 20μm is noted near the inlet. This peak concentration rapidly disperses due to action of the turbulence, and only very small centre-line concentrations are found at points further than 0.5m downstream. For the high mass loading case (twice that used in the previous calculations) the initial peak concentrations are much higher than in the preceding calculations, due to the larger impact of droplet collision/coalescence. The influence of this increase in initial concentration can be seen further downstream and leads to a significant increase in the centre-line. Clearly the inlet mass loading has a substantial effect on the spray development due to the increased likelihood of collision producing large droplets near to the inlet.

Comparison with suitable experimental data is clearly necessary, however data that isolates the effect of coalescence from other effects found in these types of problems (i.e. vaporisation) is not widely available. The two sets of results suitable for comparison allow us to draw some conclusions as to the accuracy of the calculation method compared to data obtained in an industrial setting. The overall agreement between the calculation and experiment is very encouraging. The ability of the calculations to predict the bulk characteristics of the experimental flow field is clear.

4.5 National Technical University of Athens

The slurry droplet evaporation model was performed in the standard case of BAYER pilot plant and with four different inlet conditions. The moisture mass content (‘slurry’) used, which is defined as $X = m_w/m_s$ (m_w, m_s are the masses of moisture and solids in the droplet), had an arbitrary value of 3.0. The porosity of solids’ material according to Elperiv and Krasovitov was 0.40 and the critical values for the diameter and the moisture content of the droplets were set to a standard. The predictions indicate that the gas temperature increases and the vapour mass concentration decreases due to the existence of the slurry particles which have lower overall evaporation rate. As far as the four different arrangements of the proposed Design2 of the BAYER spray dryer concerns, the differences are not very well defined, but the introduction of slow air in the perimeter of the cross-section seems to produce the best result of all as the energy efficiency concerned. The collision-coalescence and slurry droplet evaporation models have been incorporated into the NTUA CFD code and tested by predicting the flow processes in the standard BAYER spray design. The initial conditions for the airflow and the spray injection remained the same as in the standard BAYER spray design that had been previously predicted by taking into consideration only the buoyancy effects. The value of moisture content (water mass/solid mass) of the particles with solid burden was infinite and 3.0. The introduction of the collision-coalescence model into the code had an effect on the results obtained by the previous calculations for the gas and droplets characteristics, especially in the case of the lower moisture content. The gas temperature increases and the vapour mass concentration decreases due to the existence of the slurry particles which have lower overall evaporation rate.

The introduction of slurry particles into the spray dryer changes a lot the behaviour of the characteristics of the particles, especially in the temperature and the diameter. This is especially important when the product changes from the first drying stage to the second one, which can be seen good by presenting the values of moisture content (‘slurry’) of the particles along with their critical moisture content, which is 1.55 in the studied case. From this point, the evaporation rate changes from the first stage to the second stage and the particles start to raise their temperature.

5. Exploitation plans and anticipated benefits

5.1 Shadow Doppler velocimeter for industrial heated flows

The shadow Doppler velocimeter is not available commercially. Imperial college can provide measurements using the developed SDV in industrial flows, which can directly determine the optimum conditions for industrial processes. This could lead to higher quality production, more efficient emissions control and higher production efficiencies. Moreover, the development of the apparatus widens the use of the SDV for pure research purposes. The developments allow measurements in larger experimental set-ups and in denser flows. The use of such apparatus gives the Fluid Mechanics Section of the Imperial College Mechanical Engineering department the ability to continue providing the industry with cutting-edge research.

5.2 Computational calculations of spherical particle images

The Code predicts the accuracy of the optical instrumentation by rigorously computing the image of homogeneous spherical particles, taking into account: the particle diameter, the particle complex refractive index, the polarisation and shape of the incident beam(s), the particle location inside the beam(s), the imaging optics (focal length and diameter), and the detector location. This method allows the modification of optical instrumentation with predicted results, thus minimising the time required for experimentation when an optical instrument is developed or modified. Such a code is of interest to commercial companies, which develop or use optical instrumentation or to institutions which use such apparatus for research. Such a code must be viewed as an "etalon", permitting a very accurate evaluation of the signal-processing scheme in the domain of imaging of clouds of spherical particles. Then the main users of such a tool are researchers in metrology of particles and industrial designers of particle sizers. The development of this code will provide various publications at exhibitions, conferences, in professional and scientific journals.

5.3 The NTUA CFD code

The NTUA CFD code that has been developed and widened during this project is directly competitive with the state of the art commercial CFD codes through the constant comparison that has been performed in the project. The results and conclusions derived were used for improving modelling practices in other research areas currently of interest to the partners in the consortium. The CFD code could be used for comparable validation of numerical processes used in other areas of industry which have physical similarities with the mechanisms involved in spray drying. A market analysis was made regarding industrial processes involving two-phase flows with heat transfer, evaporation and liquid sprays with solid burdens (e.g. painting processes, coating formation on complex surfaces etc.). A university code has obvious advantages over commercial codes in implementing new modelling practices and testing complex methodologies. Pinpointing the areas of industry whose processes are similar to those studied in spray drying will lead to contacts and possible collaborations so that the design and research procedures can be improved. Furthermore, in the context of Category C of exploitable results, the computer code could be available as a marketable software product provided that the tasks of making a user friendly software environment and the marketing procedure are taken on through outer-university collaborations. Searching for such partners and performing a market study are also tasks that must be considered for this type of exploitation.

5.4 Cranfield University agglomeration model

All applications, that include a study of sufficiently dense two-phase flows, could benefit from this result. Users of the model would include equipment designers and code developers in the process industry and automotive sectors. The innovative features of the model are its ability to simulate the development of a spray in a computationally efficient manner while retaining the correct statistical features of the problem. However, the main barrier to the widespread use of the model is the need for implementation in commonly used commercial CFD codes. In addition the current lack of suitable experimental test cases available for validation may slow the uptake of this type of collision/coalescence model by code vendors and end users.

5.5 New design methodology for spray dryers

5.5.1 Benefits

The benefits of the new spray dryer design methodology are as follows:

- improved product quality as a consequence of
  - improved flow pattern
  - less deposits on dryer walls
  - improved product temperature control
- increased product yield
- increased production rate
- increased energy efficiency
- availability of newly developed tools for trouble shooting in spray dryer plants
- new methodology for retrofitting of old spray dryers
- new design methodology for new spray dryer concepts

5.5.2 Retrofitting of old Spray Dryers

The use of these benefits leads at first to retrofitting activities for spray dryers in the Bayer group:

- Bayer will use the newly developed tools for a world-wide review of all-important spray drying operations of the Bayer group. During checking of these facilities we will identify all cases with potential for energy saving and product quality improvement.
- On demand all above described tools and methods for the analysis of production problems will be used after gathering information of the performance of Bayer spray dryers
- After this analysis and identification of potential improvements action plans for the realisation of all suited details (e.g. flow pattern, nozzle arrangements, temperature profiles, etc.) will be proposed after intensive discussion with project partner NIRO. This close contact to all competent project partners increases the acceptance of the above-described proposals.
- These project proposals will then be presented to all concerned plant managers
- At the end of a successful retrofitting according to our methodology Bayer will run spray dryers with leading edge technology.

5.5.3 Design of New Spray Dryers

NIRO A/S intends to use the new Design Methodology in two slightly different but related ways:

- A review of all existing plant concepts that are being used for production or processing of heat sensitive products or substances, such as dairy products, food products, pharmaceuticals and certain products of the polymer industry.

- A systematic approach to the design of new and improved plant concepts for the same range of products where heat sensitivity plays a major role in the definition of the process parameters.

The new Design Methodology, comprising the NTUA slurry droplet evaporation model and the Cranfield collision/coalescence model in combination with the Heat Damage Index Number (HDIN), provides an effective and informative tool for assessment of the intensity of the process as well as the heat sensitivity aspects of product quality. The main purpose of using the new Design Methodology will be to search for improved energy efficiency of the spray dryers by changing the process parameters without detrimental effect on product quality.

The new Design Methodology has its only implementation in the NTUA CFD code that has been developed and expanded during this project. This fact poses a problem to be solved in order to achieve wide exploitation of the results of the project. The NTUA code is competitive with and in certain aspects superior to the state of the art commercial CFD codes. But it will be necessary to attempt implementation of the Design Methodology in a commercial CFD code, mainly because the two tasks defined above will require a very large amount of very time consuming calculations to be carried out.

It is a fact that all use of the new Design Methodology will be based on a pre-calculation definition of spray dryer geometry and process conditions. Before the CFD calculation can be initiated, the spray dryer geometry must be processed in a grid generator. The following CFD calculation is very time consuming and although the concept of HDIN will allow an immediate comparison of different cases, great care must be shown to make sure, those cases being compared on equal terms. The combination of spray dryer geometry definition, grid generation and CFD calculation becomes very time consuming and, in the opinion of Niro A/S, favours the use of a commercially available code.

A logical plan to accomplish the abovementioned two-way use of the Design Methodology will therefore be the following steps, which must not necessarily be carried out in succession, but may be pursued in parallel:

- Investigate possibilities for implementation of the new Design Methodology, comprising the NTUA slurry droplet evaporation model and the Cranfield collision/coalescence model in combination with the Heat Damage Index Number (HDIN) concept, in a commercially available CFD code with due respect of the intellectual property rights (IPR) of the originating partners.

- Launch a systematic effort to derive information about product heat sensitivity and heat damage rate from already existing database on product and substance properties.

- Launch review of the existing plant concept mainly applied for production or processing of heat sensitive products in the dairy industry with the purpose of generating experience with grid generation and CFD calculation procedure in order to obtain reliable data background for design changes in industrial plants.

- Launch series of pilot plant and industrial field tests to validate results of generated data with specific reference to reduce product heat damage or increase energy efficiency

- Proceed with abovementioned two main applications of the new Design Methodology.

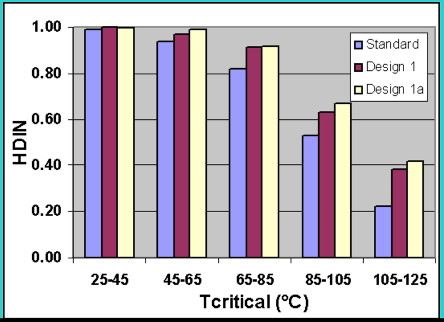
6. Figure

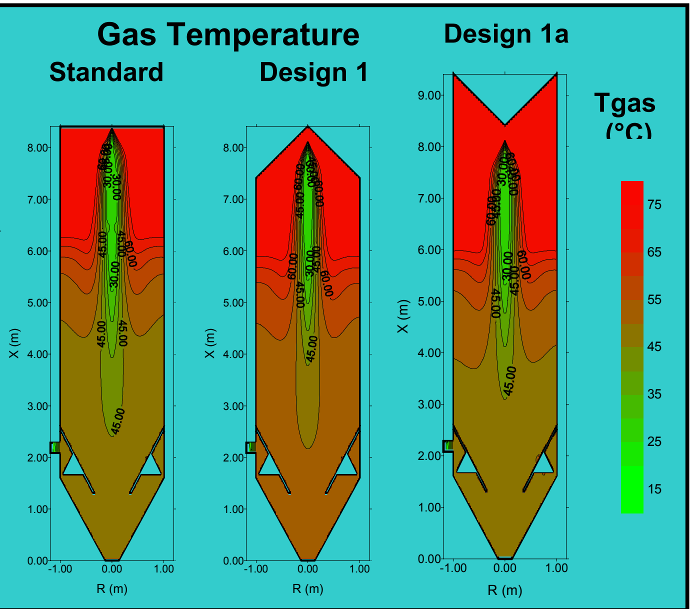
- **Improved, validated CFD-code**
- **Meaningful index number**

⇒ **Design methodology for energy efficient, intensified spray dryers**

$$H_{cr}^{*} = \frac{\sum H_T dt}{\sum dt}$$

$$HDIN(T_{cr}) = \frac{\sum H_{cr}^{*} \rho_{i,end} d_{i,end}^{3}}{\sum \rho_{i,end} d_{i,end}^{3}}$$





Development of SDV to measure particle size and velocity

Computation of pathway in and accuracy of SDV

Measurement of

- **evaporation rate**
- **scalar mixing**
- **spray drying (lab. scale)**

Development of coalescence/ agglomeration model

Measurement in industrial scale spray dryer