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CFD model of a lab scale cryogenic batch freezer with the investigation of varying effects on the heat transfer coefficient

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Abstract

Cryogenic freezers are commonly applied in the food processing and healthcare industries, and offer a highly effective preservation method without significant product degradation. The modelling of freezers has been conducted mainly around food processing, to observe the cooling rate during the chilling process. Typically, cryogenic freezers operate with a mix of air and nitrogen as the working fluid, with the effects on the heat transfer coefficient being thoroughly noted, in a range of applications. The effect of the heat transfer coefficient has not been investigated in a liquid nitrogen application, with a cryogenic applicability. This paper will focus on the CFD visualisation of the circulation of air around a lab scale cryogenic batch freezer. The effect of the heat transfer coefficient will be investigated in a number of scenarios, such as shelf loading conditions, product configuration and thermal profiles. The cryogenic batch freezer will be simulated in a range of room temperatures starting from -70°C, using a thermal profile which was obtained experimentally.

Keywords: CFD; freezer; cryogenic; lab-scale

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1. Introduction

Cryogenic freezing has been applied in a vast range of industries such as food preservation and tissue preservation, with the most common application method being in the food preservation field. With recent advancements in technology, modern numerical methods can now be applied to cryogenic freezing modelling. Modelling techniques such as Computational Fluid Dynamics (CFD) allows the study of air and heat distribution in freezing applications. The inaccuracies of numerical techniques surrounding the batch freezing process imply a risk of uneven distribution of air around the system. Research into heat transfer models, both experimental and numerical; have been proven to be mainly focused on cooling, with limited models associated with the study of freezing [1].

An investigation by Kondjoyan [2] highlighted the substantial variation in temperature, by approximately 30%, dependent on the geometry of the product and flow regime. A number of factors affect the heat transfer coefficient such as surface area, temperature difference and amount of heat transferred, and these are quantified by the size and geometry of the product alongside its placement and flow direction. The scalability of batch freezers is vast, with some systems being able to preserve whole carcasses. A significant amount of experimental investigations have simulated the impact of small and large scale items. For larger items, Kondjoyan et al. [3] highlighted a significant amount of localised heat transfer on a number of surfaces with a high level of variation between surfaces. Typically, the ideal geometry would need to be a series of flat plates, spherical and cylindrical structures, but in reality this is impossible [2].

Correlations to evaluate the heat transfer coefficient highlight the relationship between the increase in its value and the size/shape of the product, with the gradual increase of air velocity. Although the general correlation briefly determines the heat transfer coefficient between certain geometries and produce, there is no heat transfer correlation for complex geometries such as carcasses. The effect of product placement within a batch freezer poses the same issues as product geometry. The heat transfer coefficient is dependent on the angle and the amount of turbulence produced during the operation. The most successful arrangement has been a series of cylindrical tubes lying adversely to the flow direction, to disrupt the flow. This ideal arrangement does not reflect the ideal arrangement for realistic items. A number of experimental studies investigated the placement of real food items, but no clear correlation was made. The lack of correlation between items during different scenarios was attributed to the different development of the boundary layer on non-conventional shaped bodies relative to cylindrical/spherical structures [2]. Other effects such as packaging play a crucial role in the heat transfer coefficient. Typically, the addition of packaging lowers the heat transfer coefficient due to the insulative properties of the air in-between the product and packaging, but this has not been largely investigated. Additional investigations have been conducted to study the change in heat transfer coefficient in packaged and unpackaged items in a number of flow regimes [4, 5]. It was concluded that the addition of packaging increased the resistance compared to unpackaged items, although other influences such as air content and moisture within the product also play a crucial role. The identified issues have been applied to different problems such as food substances, but have not been applied to mimic biochemical fluids and the associated study on the heat transport coefficient. The modelling of biochemical substances has not been widely simulated due to the level of complexities existing within the mixture, and the lack of thermal properties available. The idea of tissue preservation has been at the forefront with storage being investigated with a number of storage techniques, but some configurations and systems may be ineffective and uneconomical causing a deteriorating product quality [6]. The storage of blood plasma in conventional ways can suffer similar effects such as varying product quality, but investigations of such a system are not easily available. The lack of modelling studies of the cryogenic storage of biochemical products leads to an inaccurate representation of the heat transfer mechanism, meaning that an improved storage system has not been investigated.

This paper focuses on the CFD visualisation of the circulation of air around a lab scale cryogenic batch freezer. The effect of the heat transfer coefficient will be investigated in a number of scenarios, such as shelf loading conditions, product configuration and thermal profiles.

2. CFD Model

2.1. Model Parameters

The geometry of the model is based on defining the rotating fan geometry, enclosed within the original freezer model. Glycerine bags were set at an ambient temperature of 16°C. An UDF was compiled to define the temperature profile of the freezer during operation, from 15°C to -70°C.

2.2. Geometry, Boundary Conditions and Numerical Method

In an ideal scenario, a Direct Numerical Simulation (DNS) would be ideal for modelling such flow profiles but the computational effort required is far beyond the resources of industrial applications. So, commonly the use of RANS models allows the flow visualisation during operation and also the interaction between blade and fluid. The available selection of turbulence models is capable of producing accurate results for heavily swirled flows and heat transfer. Previous works have suggested the utilization of k-epsilon, k-omega and the shear stress transport (SST) model. The simulation of the batch freezer was conducted using the realizable k-epsilon model using scalable wall functions. The application of scalable wall functions maintains the accuracy of the results with a fine mesh. The addition of wall functions maintains the integrity of the mesh, which is prone to deterioration under a heavily swirled flow and changes around the viscous sublayer, which may lead to an unstable simulation. The simulation was set under transient conditions with a time step size of 30s for 38 time steps. The selection of time steps is based on the time needed for the freezer to reach -70°C, which is approximately 19 minutes. A pressure-velocity coupling was set as the boundary conditions with a SIMPLE discretization method.

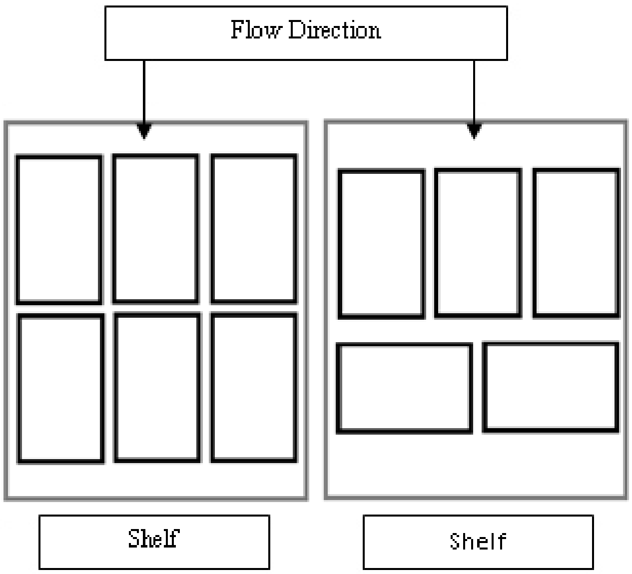


Fig. 1 Proposed shelf configuration

The placement and stacking of glycerine play an important role within the effectiveness of storage, with the optimum location being crucial to an even thermal distribution. The placement of glycerine bags follows the stacking configurations shown in Fig 1. The two generic configurations chosen reflect the most common placement techniques due to the economic advantages of the placement. The subsequent simulations were conducted with both shelf configurations and both stacking regimes, along with a proposed and optimised shelf stack/location.

3. Results and discussion

The subsequent results were obtained under the assumption of a fully loaded shelf, i.e. a shelf configuration containing the maximum amount of glycerine bags, unless stated otherwise.

3.1. Effect of Bag Placement

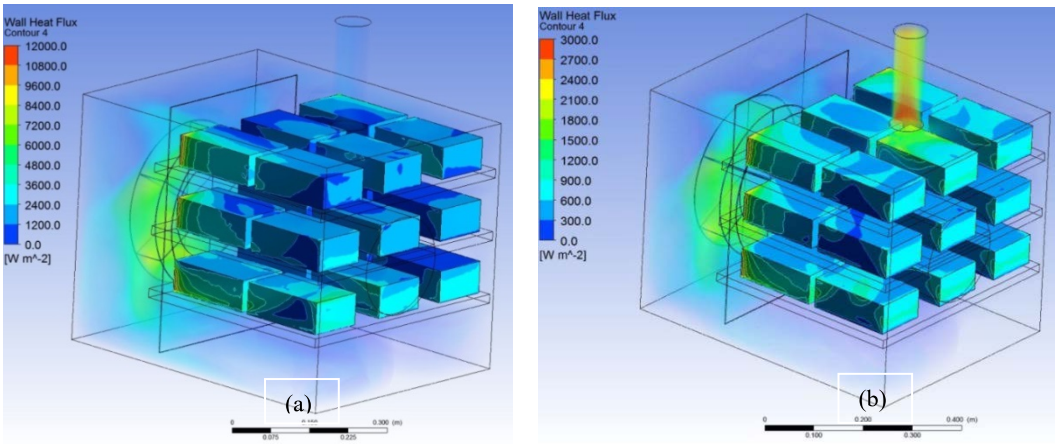
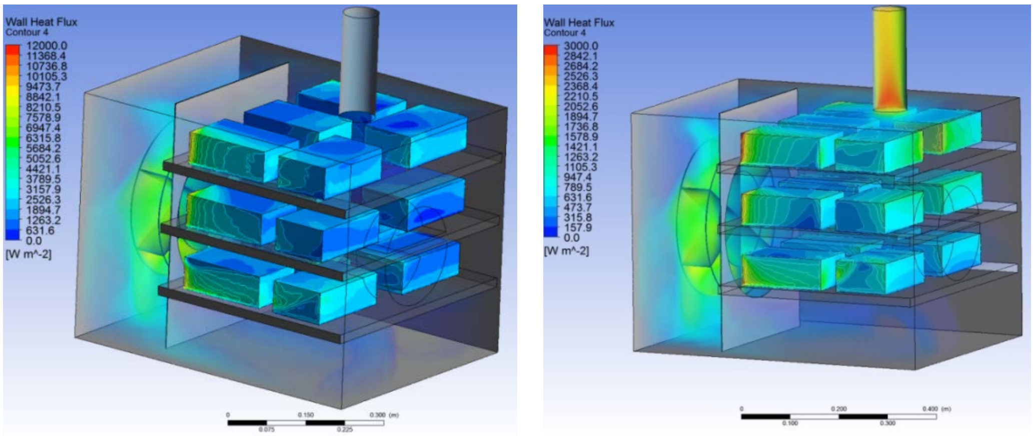


Fig. 2 (a) Wall Heat Flux in Shelf (Configuration 1) at 1995 RPM (b) Wall Heat Flux in Shelf (Configuration 1) at 285 RPM



(a) (b)

Fig. 3 (a) Wall Heat Flux in Shelf (Configuration 2) at 1995 RPM
(b) Wall Heat Flux in Shelf (Configuration 2) at 285 RPM

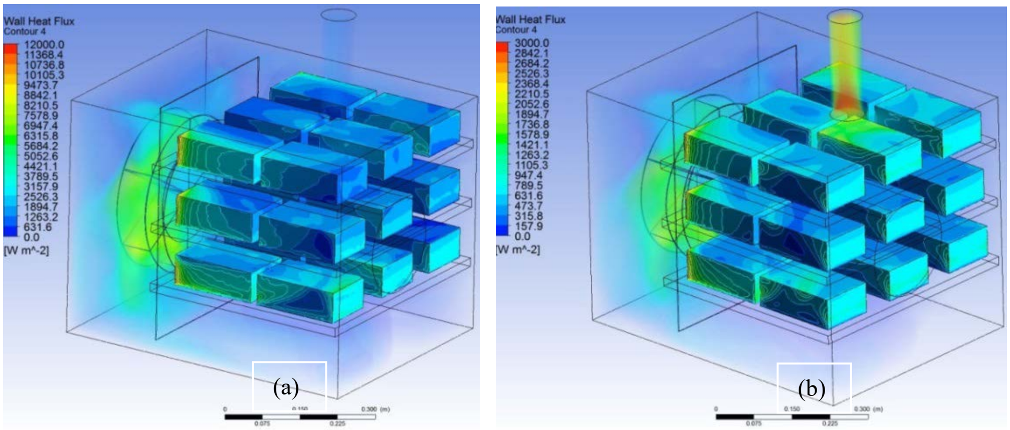
The simulations were conducted under the same conditions such as bag temperature, air temperature and pressure gradients, with the fan speed (RPM) being the only physical variable in the study. Fig. 2a and 2b reflect the averaged heat flux of the applied thermal profiles of 1995 RPM and 285 RPM, respectively. Fig. 3 reflects the corresponding information with an alternative shelf configuration. The increase in fan speed drastically increases the heat flux as predicted in many previous studies. From the initial prediction, areas with a low heat flux have been identified as the glycerine bags located towards the outer edge of the system, i.e. bags placed further away from the fan. This is evident in the study, but the alteration in bag placement results in the heat flux in those areas being increased, as shown in

Fig. 3a. In comparison to Fig. 2a, the overall heat flux in the system contains a higher percentage of thermal irregularities on the upper surface of the stacks. The production of these irregularities can indicate that the placement of these bags under the flow regime is unsuitable due to the evident lack of recirculation in those zones. The presence of irregularities can contribute to a less effective system and compromise produce. Although shelf configuration 1 (Fig. 2a) contains a higher heat flux compared to Fig. 3a, the areas of low heat flux are problematic. Fig. 2b and 3b highlight similar trends, with fewer areas of low heat flux; the overall heat flux within the system is lower by a considerable factor, which makes the system uneconomical to run. The aspect of running a low RPM operation could be used within tissue preservation but the lower velocity will cool the glycerine bags slower. To improve the freezing of the glycerine bags, the composition could be altered to increase the moisture content, but this will change the heat transfer properties of the biochemical substance and the accuracy of freezing characteristics. The implementation of a low RPM system could be used where quick freezing is not needed.

3.2. Effect Of Stacking

The effect of stacking has been investigated in both shelf configurations, a single stack and a double stack, with high and low frequency values.

Fig. 4 (a) flux of a stacked

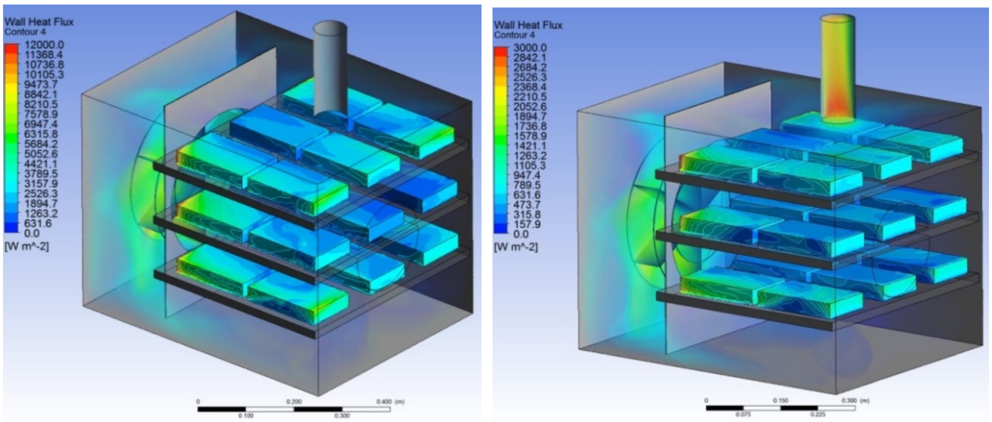


Wall heat double shelf (shelf

configuration 1) at (1995 RPM)

(b) flux of a stacked

1) at (285

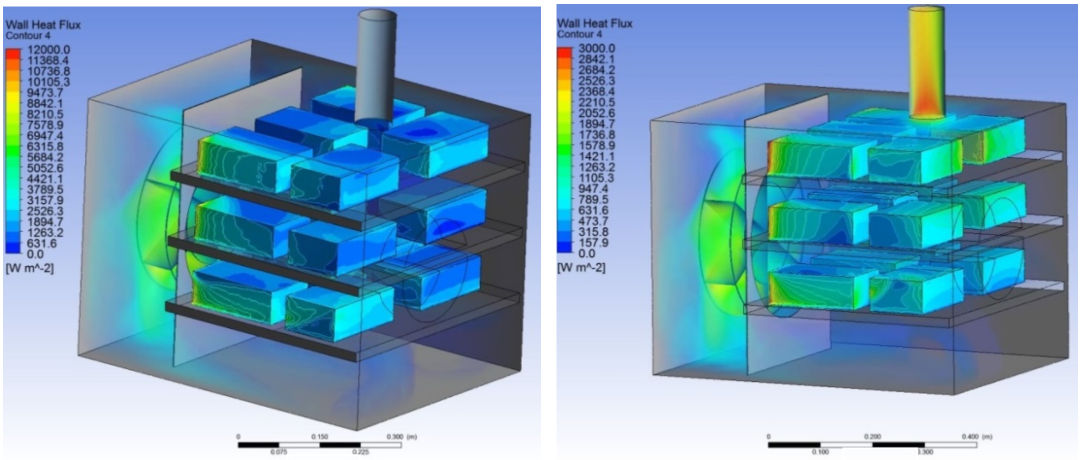


Wall heat double shelf (shelf configuration RPM)

(a) (b)

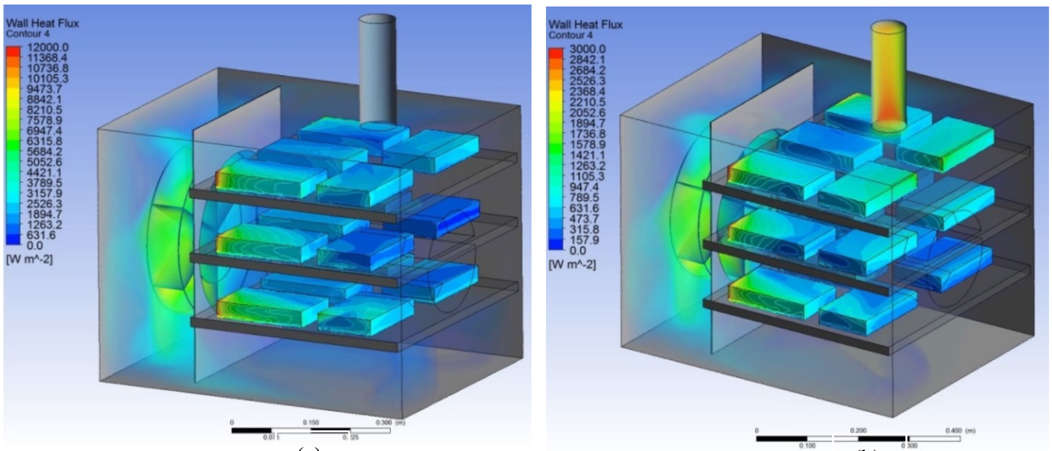
Fig. 5 (a) Wall heat flux of a single stacked shelf (configuration 1) at 1995 RPM
(b) Wall heat flux of a single stacked shelf (configuration 1) at 285 RPM

The effect of stacking has been initially investigated for shelf configuration 1. Theoretically, a single stack should perform better than a double stack, which is evident in Fig. 5a and 5b in comparison with Fig. 4a and 4b. The differences between single and double stacking are quite significant but, unlike other high frequency simulations, Fig. 5a shows a relatively distributed heat flux and the most promising results, with a similar maximum heat flux as its double stacked counterpart. The major fluctuation in heat flux towards the edges of the shelves could be due to a number of factors such as lack of recirculation in the specific region. To improve the recirculation and maximise the effectiveness of the system, additional shelves could be added with a reduced gap, eliminating the role of stacking. The addition of small shelves could produce similar effects to stacking without the physical stacking.



(a) (b)

Fig. 6 (a) Waii heat flux of a double stacked shelf (configuration 2) at (1995 RPM)
(b) Wall Heat flux of a double stacked shelf (configuration 2) at (285 RPM)



(a) (b)

Fig. 7 (a) Wall Heat flux of Single Stacked Shelf (configuration 2) at 1995 RPM
(b) Wall Heat flux of Single Stacked Shelf (configuration 2) at 285 RPM

The addition of stacking proves to be the preferred method of storage but the associated heat transfer coefficient suggests the opposite. The addition of stacking shows a higher variance in heat flux leading to a larger amount of product variation. Shelf configuration 2 is not the most effective method of storage at high frequencies. This is also evident for single stacking methods. Commonly, singular modules perform better than their stacked counterparts, but the configuration and stacking shown in Fig. 7a indicates a similar pattern but with a greater variance in certain regions. The effect of single stacking in that specific area may not be suitable, with the double stack configuration showing a relatively more constant result for that region as shown in Fig. 6a. Both double and single stacked configurations show a significant amount of variation, with the single stack providing a higher heat flux. The concept of selective stacking might prove to be more effective, and a good compromise with a more even thermal distribution.The overall heat flux for a single stacked system under a high RPM is possible but needs a slight alteration in the bag location. The single stack shown in Fig. 5b and 7b proves to be more effective in specific low heat flux areas. In the low fan speed setting, the results are similar to the previous investigation. The low RPM fan speed setting provides a relatively uniform distribution compared to the high frequency simulation, with no major localisation of low heat transfer coefficients. The low frequency simulation provides the most uniform heat flux, and can be utilised in applications where quick freezing is not necessary.

3.3. Discussion

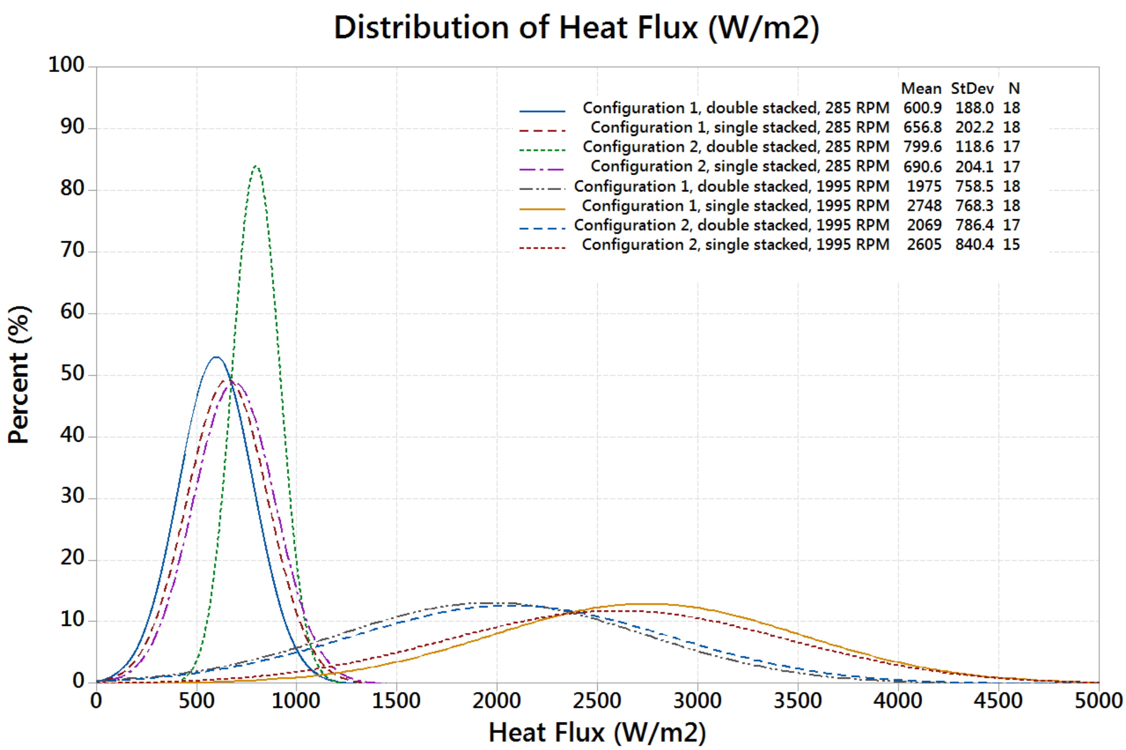


Fig. 8: The distribution of heat flux in the glycerine bags in the applied scenarios

Fig. 8 presents the heat flux distribution and the variation in heat transfer in the glycerine bags in each shelf loading/configuration, for different fan speeds. The applications regarding low RPM simulations are clustered around the lower end of the heat flux spectrum, but show a higher amount of uniformity compared to the high RPM counterparts. Both peaks of configuration 1, double stacked, 285RPM (Fig. 4b) and configuration 2, double stacked, 285 RPM (Fig. 6b) show promising results, with the largest amount of regularity compared to the single stacked counter parts. The increase in heat flux between each low RPM can be due to the increase of surface area between single stacked and double stacked components. The results highlighted in Fig. 6b indicate the most effective and economic scenario with the largest amount of regularity compared to all other scenarios. The standard deviation between the data is 118.6 W/m^2, and maximum heat flux in comparison to the other low RPM scenarios. The application of low RPM storage is acceptable when fast freezing is not important. In comparison to high RPM scenarios, the regularity is significantly less due to the increased instability, this can be due to many factors such as bag placement and the effect of stacking as mentioned previously. The addition of further bloodbags is determined by their positioning. Both configurations 1 and 2 of the double stacked scenarios under a high RPM (Fig. 4a and 6a, respectively) show lower heat fluxes of approximately 1,975 and 2,068 W/m^2, indicating that the effect of stacking can minimise the recirculation in specific zones. This is evident in the single shelf counterparts Configuration 1, single stacked at 1995 RPM (Fig. 5a) and Configuration 2, single stacked at 1995 RPM (Fig. 7a), which show a significant increase in the heat flux without the relative comprimise in regularity. The removal of the additional stack improved the circulation around the freezer space, whilst achieving a higher heat flux. Both configurations are successful and viable with the average difference between them being 143W/m^2, with Configuration 1, single stacked at 1995 RPM (Fig. 5a) being the scenario with the highest heat flux. Futher design modifications and improvements could be the adddition of shallow depth shelf spaces to maximise the space within the freezer without the negative consequences of a stacked shelf configuration.

4. Conclusion

The determination of the optimum location of glycerine bag storage is a complex task due to the amount of combinations and operation settings available. There is a strong correlation between our simulations and the literature, in that the location and placement of the bags play a crucial role in the effectiveness of the system. From the observations made, the performance of single stacked shelves was better with a minor amount of low localised heat flux. From the study, the most successful placement and configuration was Fig. 5a (Wall heat flux of a single stacked shelf (configuration 1) at 1995 RPM) due to the relatively even distribution and associated heat flux. The results show low localised areas of heat flux which could be corrected by a number of methods, such as change in bag location and the implementation of additional shelves, although the realistic addition of single shelves is not economical due to the amount of unutilised space for the size of the system. The concept of stacking is much more economical as the amount of unutilised space is reduced. The addition of other shelves with a smaller depth could provide the same thermal characteristics as stacking. The simulation conducted only investigates the effect of two shelf configurations, with a large amount of alternative configurations still to be investigated such as the effects of staggering and alternative storage methods. These effects are yet to be investigated alongside other frequencies. The results of the CFD simulations are still to be validated against experimental data.

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