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Application Of Refrigeration Technologies For Energy Efficient Production Of Fish Protein Hydrolysates

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ABSTRACT

Fish protein hydrolysate (FPH) is one of the most efficient and sustainable way to recover the valuable nutrients from fish remaining materials and has a widespread application. However, the production of FPH demands intensive heating and cooling loads in the temperature range between 0 and 90 ^{0}C. In addition, the stabilization of FPH using conventional moisture removal techniques like spray drying and evaporators is energy intensive due to low solid content. This study investigates application of refrigeration technologies and heat pumps to determine sustainable and energy efficient methods for processing and stabilization of FPH. The freeze concentration, vacuum-concentration and freeze-drying processes were investigated in combination with energy recovery at high temperatures (heating and sterilization). The overall comparison of production lines with respect to the energy savings of different techniques was presented.
Keywords: Fish protein hydrolysates (FPH), Industrial drying techniques, vacuum freeze concentrator, vacuum drying, Heat pump drying, Energy savings.

1. INTRODUCTION

Fishing sectors produce significant amount of fish rest raw materials which greatly contribute to environmental impacts owing to its disposal factor. These by products are used for low value products in the market. However, the high protein source of fish waste and its by-products can be used to produce valuable products like Fish Protein Hydrolysates (FPH) (Desai et al., 2022).

The liquid state of FPH has a high water content, which is relatively unstable and reduces shelf life. Hence long-term storage and transport is not possible. The removal of moisture from FPH is complicated and expensive. Drying can be performed using spray dryers, drum dryers which remove the moisture down to 1-3% (Petrova et al., 2018). Conventionally, spray dryers are widely used in industries, but they are large energy consumers, with energy consumption up to 11.5 MJ/kg of water removed (Mujumdar 2007). With the efficient techniques the specific energy consumption was reduced upto 5.5MJ/kg of evaporated water (Mansour et al., 2011). Several studies reported vacuum freeze-drying method is suitable for temperature sensitive products.

Evaporation methods can be used for concentrating the FPH as well. Among the energy efficient techniques, multistage evaporation (MSE) method, Mechanical vapor recompression (MVR) method, energy reduction is mentioned. Han et al. (2021) experimentally investigated the MVR system and concluded that with two effect evaporator 40% more energy saving was achieved when compared with single-stage MVR system. Jeantet et al. (2015) studied the energy consumption in the processing of dairy and feed powders by vacuum evaporation and spray drying methods and established calculation models in computing the energy consumption in the dairy industry. They observed that, to produce 1 kg of dairy powders the energy costs were 6.1 MJ/kg powder for pregelatinized starch and soy protein concentrate respectively.

Concentration processes must be performed before the final stages of product drying to lower the drying cost. Freeze concentration technique is performed to lower the overall energy consumption rate in the production of FPH. Miyawaki et al. (2005) in their research work reported, that the freeze concentrators consume energy of around ~ 0.3MJ/kg of water to freeze. Heat pumps are energy efficient technologies which can be used to provide integrated cooling and heating. Using heat pumps, waste heat from other processes can be recovered and can be upgraded and reused effectively. Studies related to integrated heat pump application system in the production of fish protein hydrolysates process is limited. From the above literature review, it is identified that research findings related to energy conservation and application of heat pumps in the production of fish protein hydrolysates are available in scanty. Hence, in this present study, the main objective is to identify the energy use in each process, identifying the process with high energy use and suggesting the energy reduction measures.

2. EXPERIMENTAL METHODS

The process flow diagram of the production of fish protein hydrolysates with different concentration and drying alternative techniques is given in Figure 1. To have a better view on energy use, the concentrating methods are compared in combination with drying methods. Conventional methods like spray drying and evaporators are compared with methods like freeze concentration, vacuum freeze drying, and heat pump assisted drying. The energy study involves a detailed investigation of freeze concentration, evaporation in the concentrating process and drying using spray drying method, vacuum freeze drying, rotary drum drying, heat pump assisted drying.

The study was performed for 1000 Kg/h of rest raw material (RRM) and 1000 kg/h of water (1:1 ratio). At all levels, the mass flow and energy flows were analysed. The initial composition of RRM is given in Table 1: (Petrova 2018). Two types of RRM (chilled and frozen) were used in the production of hydrolysates. The frozen RRM is first thawed from a lower temperature of -18 °C to 10 °C. Once the RRM is thawed, the next step involves grinding and mincing with water. The pre-treatment process was same for all the processing methods. During the hydrolysis process, the solution was heated to hydrolysis temperature of 50 °C and the enzymes were added to the RRM mixture.

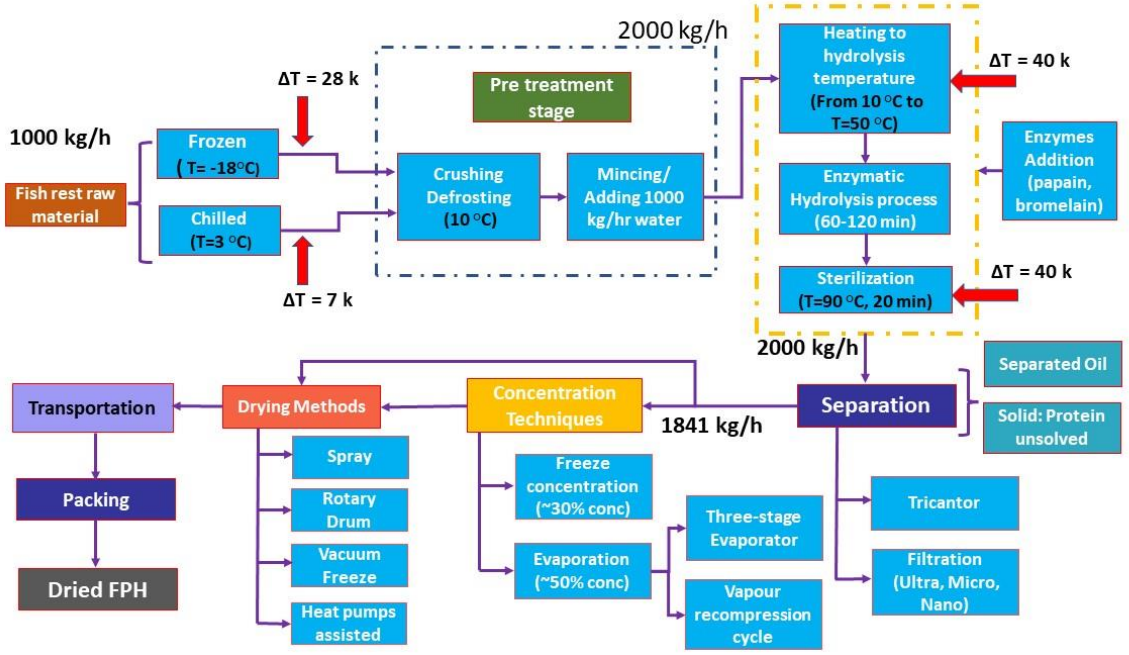

Figure 1: General process flow diagram in production of fish protein hydrolysates

Heating the mixture to the hydrolysis temperature consumes significant amount of energy. After the completion of the hydrolysis process, the temperature of the solution is pasteurized at temperature of 90 °C and the mixture was stirred for another 15-20 mins. The RRM water - mixture is then fed into the separation process. In the calculation, it was considered to have approximately 7% solids with 6.5% protein content in the FPH after separation. The protein unsolved mixture has 80% protein and 20% water. The composition of the final LPH after separation is given in Table 1.

Table 1: Composition of rest raw material and hydrolysates after separation

RRM initial composition (1000 kg/h)	Percent	Liquid FPH after separation (1841 kg/h)	Percent
Water (W)	77.7	Water	93
Protein (P)	14.6	Protein	6.583
Fats (F)	0.4	Fats	0.217
Ash (A)	7.3	Ash	0.2

2.1. Freeze concentration process

Freeze concentration is a technique that involves freezing and removal of water by fractional crystallization of water into ice. The hydrolysates were initially cooled to +4 °C from 90 °C in the freeze concentration process. In the process, the inlet mass flow rate was 1841 kg/h, the hydrolysates are concentrated at 30 % solids from the initial feed temperature of +4 °C to the final freezing temperature of -3° C.

Above the freezing temperature, the enthalpy change can be calculated as follows, by evaluating C_p above freezing point.

$$\Delta h_T = (T - T_f) * C_p \qquad \text{Eq. (1)}$$

T and T_f represents initial and final freezing temperature in degree Celsius or kelvin. The specific heat C_p value was calculated as the sum of C_p values of individual products. Below the freezing point, the change in enthalpy, Δh was calculated as follow,

$$\Delta h_{T,frozen} = (T - T_f) * \left(C_p - (x_w - x_{un,w})\right) * \left(\frac{L}{T} + (C_{p,w} - C_{p,ice})\right) \qquad \text{Eq. (2)}$$

Where L represents the latent heat of ice (333.5 kJ/kg), $C_{p,w}$, $C_{p,ice}$ represents the heat capacity of water and ice respectively which was calculated as a function of temperature, the total change in enthalpy is given by,

$$\Delta h_{total} = \Delta h_T - \Delta h_{T,frozen} \qquad \text{Eq. (3)}$$

Net heat load to be removed to freeze the product in kW was calculated as follow, Where M is the mass flow rate in kg/s.

$$Q_c = M * \Delta h_{Total} \qquad \text{Eq. (4)}$$

During the process, the heat required to melt the ice formed in freeze concentration process must be accounted. The Carnot COP and refrigeration work operating at T_h = 0 °C and T_l = - 40 °C are calculated. Where T_h and T_l represents the higher and lower temperature, respectively.

2.2. Evaporation using three stage evaporation and mechanical vapor recompression

In the evaporation process, the final solid content in concentrate was considered to be 50% for calculation. Higher solid content increases the viscosity of the product, and the evaporation process is more difficult to perform as studied in laboratory experiments. The mass flow rate of hydrolysates into the evaporator at concentration stage was at 1841 kg/h. In three stage evaporator, the vapor from the previous stage was used as a heating medium in the next stage which reduces the energy demand. The inlet temperature of hydrolysates was considered in two cases in the multistage evaporator, case 1: 90 °C, since the process is continuous and the temperature after the separation is expected to be 90 °C with no heat loss. In case 2, the hydrolysates are processed to storage temperature of 0°C. The amount of heat required to evaporate the water is given by the heat energy required to raise the feed temperature to boiling point (100 °C) and the latent heat required to evaporate from liquid to vapor which is given by,

$$Q_{net} = M * C_p * \Delta T + M_v * \Delta H \qquad \text{Eq. (5)}$$

For a three-stage evaporator, the total heat value is divided by the number of stages (three) for approximation. The mass flow rate out of the evaporator and the vapor removed are calculated using energy and mass balances. Heat load to be removed from the condensing vapor is given below, where h_3 is the enthalpy of vapor at third effect and h_{liq} is the enthalpy of the liquid at condensing temperature and pressure (0.2 bar and 30 °C).

$$Qc = M_v(h_3 - h_{liq}) \qquad \text{Eq. (6)}$$

In mechanical vapor recompression system, the vapor from the feed solution is heated using a compressor or a blower fan which increases the pressure and the temperature sufficiently for energy transfer. The energy possessed by the vapor is reutilized for heating the feed. The cycle operates at higher pressure 1.5 bar. A reheater can also be employed at the exit of the compressor based on the temperature requirements. The required heat energy to evaporate the moisture and to concentrate the feed is provided by the necessary work input to the system. The work input in kJ/kg in the vapor compression cycle is provided by,

$$W = \frac{h_{2s} - h_1}{n_{is}} \qquad \text{Eq. (7)}$$

2.3. Drying Techniques

In spray drying, the heat input (Q_t) required to evaporate the water includes (i) the heat required for sensibly heating the liquid-phase and evaporating the water, (ii) heat required for heating the solids in the feed, (iii) the amount of heat required to raise the temperature of the remaining water in the product. Additional heat required for heating the air from ambient temperature has to be considered as follows, where T_1, T_2 is the inlet and exit air temperature respectively.

$$Q_{net} = 1.25 * Q_t * \left[\frac{T_1 - T_{air}}{T_1 - T_2}\right] \qquad \text{Eq. (8)}$$

In rotary drum drying, the heat source air temperature was 300 °C and the hydrolysates are concentrated to ~98% solids. The required heat is provided by the exchange of heat between the hot air and the product. The following assumptions are included in the analysis, (i) Heat to raise the temperature of the feedstock solid. (ii) Heat lost in residual moisture; (iii) heat carried away by the amount of moisture present in the exit feed. (iv) The heat required to raise water temperature to saturated temperature. (v) The heat required to raise the temperature of the water to vapor temperature, is given by the product of the mass of vapor to the latent energy, (vi) heat loss and additional energy required for heating the air.

In vacuum freeze-drying, the sublimation of the product occurs at -20 °C inside the freezing chamber at pressure ~1.0 mbar. The product is frozen from initial feed temperature to temperature of -20 °C. After this sublimation of ice occurs, which results in the direct phase change of ice into vapor without liquid phase. The heat energy required during the process will be the difference in enthalpy between the saturated solid state to the saturated gas state of water at -20 °C and 1 mbar. The freezing load is provided by the refrigeration capacity to transform water vapor to ice on the evaporating surface. It is given by the difference in enthalpy of saturated gas at -20 °C to the solid at -40 °C at the same pressure. Other additional energy was considered in the vacuum freeze-drying is the work input to the compressor to provide the necessary cooling capacity at sufficient temperature. The Carnot COP of the refrigeration capacity is calculated at T_h = 30 °C and T_l = -50 °C. The work input of the vacuum pump to maintain relatively low pressure during the entire drying process was also calculated.

Heat pump assisted drying can provide greater energy savings for the drying process. The heat rejected from the heat pump system is used to heat air to high temperatures up to 150 °C. In our study high temperature heat pumps were considered. High temperature heat pumps can be used for drying the products effectively. Also, better products quality with a low energy consumption in controllable drying environment are achieved. Examples of heat pump assisted drying include heat pump assisted solar drying, fluidized bed drying, microwave drying, atmospheric freeze drying, and chemical heat pump assisted drying. Heat pumps works on the principle of vapour-compression cycles or absorption-compression cycles. Natural refrigerants like Ammonia, CO_2 are widely used in the refrigeration industry due to their better thermodynamic properties and reduction in environmental impacts. CO_2 booster and ejector systems are the developments in CO_2 refrigeration which increases the system performance. The simple heat pump cycle consists of a compressor, condenser, evaporator, and expansion valve. COP indicates how efficiently the heat pump is running. From an industrial point of view, higher COP reduces energy costs.

3. RESULTS & DISCUSSION

3.1. Concentration using freeze concentration

The heat load to be removed from the hydrolysates was calculated to 135.5 kW. The energy required to freeze 1 kg of water was found to be .26 MJ/Kg. The results are in accordance with studies stated by Osato (2005). The fraction of ice removed from the feed hydrolysates was equivalent to be 76.7%. Using numerical models, the initial temperature at which nucleation of ice occurs was calculated to be -0.6 °C. The heat load to melt 1411 kg/h of ice formed was calculated at 137 kW considering sensible heat above and below freezing and latent heat when the phase change occurs. In freeze concentration, apart from the energy required for freezing the LPH and melting the ice, the refrigeration work must be considered. The refrigeration work calculated during Carnot process was 30.4 kW with evaporation temperature -40 °C and condenser temperature 0 °C. The Carnot COP is 5.8. The freeze concentration method leads to reduced energy consumption, here the main principle is the crystallization of liquids, the energy required to crystallize the liquids is lower when comparing the energy for vaporizing the liquid, as the latent heat to change liquid to gas phase is higher than the latent energy to phase change from liquid to solid.

Using freeze concentration method, the hydrolysates are concentrated to 30% solid content with a mass flow rate of 430 kg/h. Further, the drying processes were performed in order to remove water completely. In the drying calculation after freeze concentration, the LPH was concentrated to 98% solids in spray, drum and vacuum freeze drying. The hydrolysates initial temperature was -1°C and the amount of water vapor removed at 298 kg/h. The drying process consumes high energy between 1.5-1.67 kWh/kg of water removal as seen below in Figure 2. The obtained calculation results are in the range with standard values at 0.8 to 5.5 kWh/kg of water removal. The high energy required during the concentrating process is due to the energy needed in raising the feed temperature close to the boiling point temperature and the latent energy for changing the liquid phase to the vapor phase.

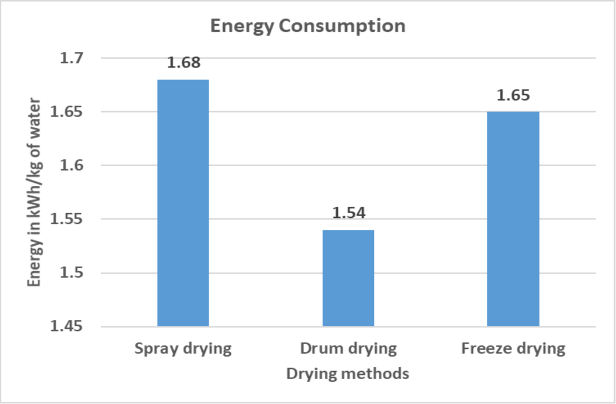

Figure 2. Energy consumption in drying process

3.2. Concentration by three stage evaporators

Multistage evaporators and vapor recompression methods are studied to identify how energy reduction can be achieved at concentration steps. The heat load calculated during the three-stage evaporator process was 338 kW when the process is continuous with hydrolysates flow temperature at 90 °C. If the hydrolysates are stored to storage temperature, the total heat load during the process was 399 kW. The concentrated hydrolysates flow at exit of the evaporator is 257.7 kg/h and the amount of vapor removed is 1583 kg/h. It was estimated that the vapor evaporated at the last stage was 527.6 kg/h calculated from total evaporating vapor with the concentrating level at each stage. The condenser was maintained at a lower temperature of 30 °C with a pressure of 0.2 bar. Cooling Load for condensing the vapor at last stage was calculated to be 364 kW. The process was further dewatered by drying methods and the corresponding heat loads are calculated as shown below,

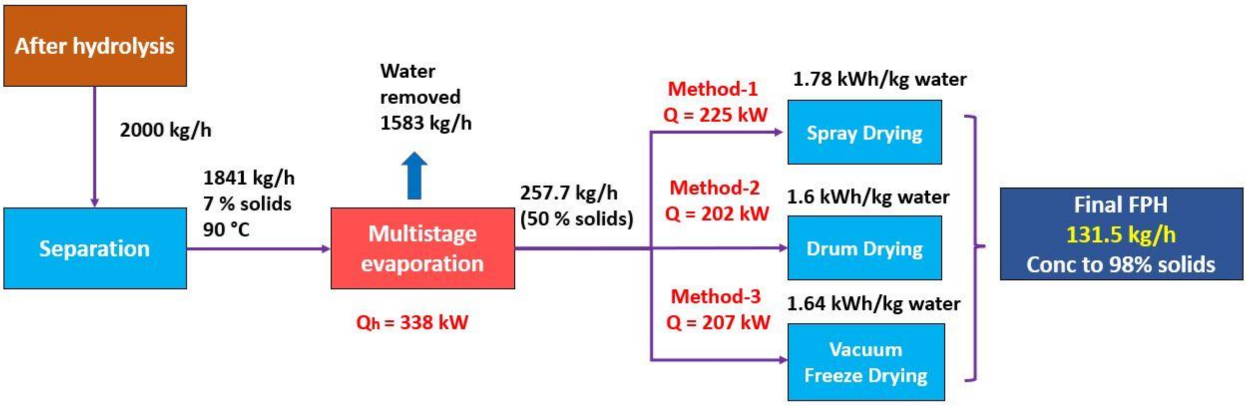

Figure 3. Process flow diagram with three stage evaporators

3.3. Mechanical vapor recompression

The work input of the system was calculated at 103.1 kJ/kg to raise the pressure from 1 bar. The heating capacity out of the system Q_c was 2310.7 kJ/kg. The compressor removes the vapor from the evaporator and increases the pressure. Energy for evaporation was returned to the system. The pressure difference of the compressor is small resulting in low energy input. Hence the COP of the system is very high at 22. The system can be operated with increase in pressure and the corresponding heat output is large. On the other hand, the work input to raise the system pressure is higher. In this process, only during starting, steam was consumed and further no external steam input was required. The process is reliable in operation, compact equipment, does not require any external heating source and higher thermodynamic efficiency.

3.4. Heat pump assisted drying

When heat pumps are integrated into the drying system, the energy efficiency of the process is increased. In the spray dryer the exhaust air has sufficient heat, which is surplus energy that can be utilized as a heat source to the heat pump. The high-temperature air is heated at the condenser side, hence lowering the amount of energy that the heaters in driers are using. The high temperatures heat pump studied in this work was used to heat the air to a temperature up to 150°C. In spray and drum drying, a significant amount of the energy was consumed by heating the drying air to the desired high temperature. Hence, calculation was performed to understand the influence of inlet air temperature on the energy consumption in the spray dryer. The heat transfer was very inefficient by heating the air from 15°C to 200°C, hence the temperature lift must be reduced. The energy variation, with respect to the inlet air temperature for spray dryer, is given below. It is observed that the inlet air temperature plays a significant role in energy consumption.

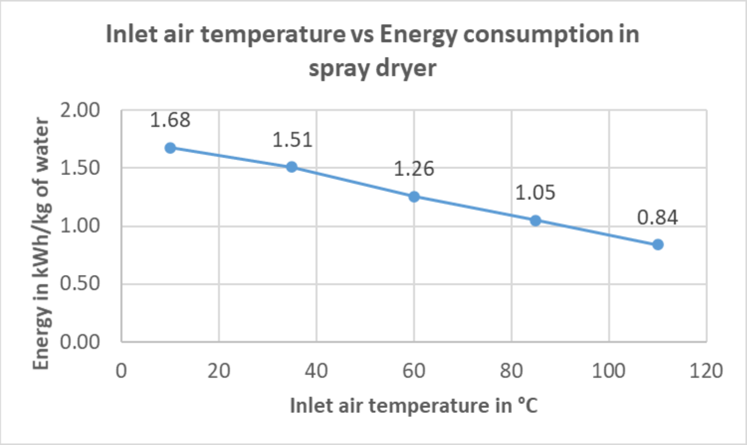

Figure 4. Spray dryer energy consumption against inlet air temperature

When the air temperature increased from 10°C to 110°C, the energy required to evaporate per kg of water was reduced to 0.84 kWh/kg ~ 3020 kJ/kg of water which is a 50% reduction in energy consumption in the spray drying process which is seen in above Figure 4. Since using high temperature heat pump, with ammonia or CO_2 as a working fluid, the energy recovery can be achieved to sufficiently heat the air to a higher temperature, this reduces the energy need for heating the air. Waste heat recovery can be an efficient option to heat the drying air which reduces the overall energy consumption. Heat pump assisted drying consumes less energy, since the heat pump cycle has higher COP. Using heat pumps the waste heat can be recovered more effectively. Implementing high temperature heat pumps in the process of production of FPH helps to cover heating and cooling needs in an economical way.

3.5. Overall energy consumption

The total energy requirement when concentrating 1000 kg/h of rest raw material to 131.5 kg/h (98% solids) is given below in Table 2. It is observed from the table, that the direct drying of FPH consumes significant amount of energy use. Hence, concentrating techniques before the final drying process should be implemented to reduce the energy demands. When concentrating 30% solids of FPH by freeze concentration and then final concentrating with drying methods, results in lower energy consumption around 1120-1245 kWh for 1 ton of rest raw material. Which is 60 % energy savings when compared with direct drying methods.

Table 2: Process wise Energy requirement (kWh) per 1 ton of RRM

		Freeze concentration	**Three effect evaporators**	**Mechanical vapor recompression**	**Direct drying**
Drying method used	**Spray drying**	1245.3	1182	629	3183
	Drum drying	1124.3	1158	606	2958
	Vacuum freeze drying	1230	1163	611	3315

Concentrating to 50 % solids using mechanical vapor recompression (MVR) method followed by drying has very low energy requirements of 606-630 kWh when processing 1 ton of RRM. For heat sensitive products, the freeze concentrating process can be widely used, as the process operates at lower temperatures. Lower process operating temperature leads to improved process efficiency and enhances the product quality.

4. CONCLUSION

In this research work, the energy consumption in the production of fish protein hydrolysates for 1 ton/h of RRM was investigated in detail. To stabilize the FPH, removal of moisture by direct drying process consumes significant amount of energy around 3000 to 3300 kWh. Freeze drying, spray drying and drum drying consume high amount of energy, between 1.5 to 1.88 kWh/kg of water. On the other hand, when performing concentrating process before final drying reduces the overall energy consumption. Freeze concentration can be used as an effective process in combination with drying and has an energy consumption of 1120-1250 kWh. With freeze concentration method 30% solids was concentrated. The main advantage is low temperature operation and reduce further energy costs. Also, in this study three stage evaporation and mechanical vapor recompression was studied with drying methods. The results showed a significant energy reduction when compared with direct drying process, the mechanical vapor recompression process consumes less energy when comparing other methods, since it works on energy recovery principle. High temperature heat pump assisted drying was studied with heat recovery, which is an effective way of integrating the cooling and heating demands.

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NOMENCLATURE

Abbreviations		**Symbols**	
FPH	Fish Protein Hydrolysates	*H*	Enthalpy [kJ/kgK]
RRM	Rest Raw Material	*Cp*	Specific heat capacity [kJ/kgK]
Hx	Heat exchanger	*Wc*	Work Carnot [kW]
CO_2	Carbon dioxide	*Qnet, t*	Heat Transfer rate/Heat input [kW]
COP	Coefficient of performance	*mf*	Feed Mass flow rate [kg/h]
ERS	Energy Recovery Scheme	*mv*	Mass flow rate of vapor [kg/h]
MEE	Multi Effect Evaporator	*E*	Energy Consumption [kWh]
MVR	Mechanical Vapor Recompression	*Lice*	Latent heat of ice [kJ/kg]
BPR	Boiling Point rise	T_{a1}	Inlet air temperature [°C]
SMER	Specific Moisture Extraction Rate	T_{a2}	Exit air temperature [°C]

Greek symbols		**Subscripts**	
ΔHvap	Latent heat of vapor [kJ/kg]	*l*	liquid
ρ	Density [m^3/kg]	*v*	vapor
η_C	Carnot efficiency -	*w*	water

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