STATISTICAL STUDY FOR CONVERSION OF GLUCOSE TO HIGH FRUCTOSE CORN SYRUP

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ABSTRACT: *High-Fructose Corn Syrup (HFCS) is a blend of glucose and fructose formed by breaking down corn starch. Fructose and glucose both have the same properties, but differ in chemical structure. HFCS has substituted table sugar (sucrose) as the primary artificial sweetener found in consumer food products. Sucrose consists of a glucose molecule and fructose molecule bonded together and can be harvested naturally from plants such as sugarcane and sugar beets. Recently there has been a lot of controversy surrounding the use of HFCS instead of sucrose; mainly that HFCS is worse than sucrose for the human body. These claims have been mostly refuted based on several studies and since both sucrose and HFCS are both made up of fructose and glucose, they are metabolized the same way. The demand for HFCS continues to increase worldwide and it will remain one of the essential food products produced for years to come. The production of HFCS is a wonderful example of a cost-effective bioengineering process. The objective of this research is to introduce the statistical analysis for the production of High-Fructose Corn Syrup from glucose. This study includes the production process of High-Fructose Corn Syrup along with the process flow diagram. The material and energy balances of the equipment employed in the whole process have also been carried out in this research.*

Key Words: Glucose; Fructose; Corn syrup; Sucrose; Carbohydrate.

1. INTRODUCTION

High-fructose corn syrup (HFCS) is a liquid sugar option in contrast to sucrose utilized in numerous nourishments and drinks. The HFCS is a sweetener formed using corn and can be found in various nourishments and beverages on the market retire in the United States [1, 2]. It has been made out of either 42 percent or 55 percent fructose, with the rest of the sugars being glucose and higher sugars. As far as structure, HFCS is about indistinguishable to table sugar (sucrose), which was made out of 50 percent fructose and 50 percent glucose. Glucose is one of the least complex types of sugar that fills as a building block generally for carbohydrates. Fructose is a straightforward sugar ordinarily found in foods grown from the ground [3, 4].

Sucrose is disaccharide, which means two single sugar molecules, monosaccharide, reinforced together. In the small digestive tract, that bond is part to yield one molecule of glucose and one of fructose. Whereas HFCS contains fructose and glucose, however, they are not bonded together. Moreover, the fructose or glucose are expended as disaccharides or monosaccharide, both are absorbed from the instant in the single molecule structure. At the point when contained in acidic media, for example, most carbonated drinks and lemonade, sucrose usually separates into glucose and fructose particle. Along these lines, when sucrose-improved refreshments were expended, many, it contains a substantial measure of free glucose and fructose, basically the same as HFCS [5, 6].

Table 1: Composition of different sweeteners

Component Percentage	HFCS-42	HFCS-55	Sucrose	Invert sugar	Honey	Corn syrup	Fructose
Fructose	42	55	50	45	49	0	100
Glucose	53	42	50	45	43	100	100
Other sugar	5	3	0	10	5	100	0
Moisture	29	23	5	25	18	20	5

Corn is high in starch, which is a chain of glucose molecule held together. Exactly when the chains are broken isolated, single glucose molecules were released and structure glucose syrup. During the 1970s, analysts made sense of how to change over glucose into fructose, and the resulting thing was named high fructose corn syrup. In spite of the fact that accurate in regard to the term glucose syrup, the name high fructose corn syrup has, consistently, been a wellspring of chaos for the purchasers and researcher alike [7, 8]. Since the presentation of HFCS, wellsprings of caloric sweeteners have moved in the U.S. Amid the 1970s, sucrose was the essential sugar [9]. At the point when HFCS was developed, it was explicitly figured to give sweetness proportional to sugar. All together for food and beverage creators to utilize HFCS instead of sugar, it was critical that it provides a similar dimension of sweetness as sugar with the goal that customers would not see a distinction in item sweetness and taste. During the 1980s, when soda organizations embraced HFCS into their mark colas, HFCS use started to supplant refined sugar (sucrose) in the food supply [10]. Beginning in 2005, about 42% of the per capita sugar supply is HFCS. Reflecting the globule in caloric sugar per capita accessibility, HFCS per capita accessibility, balanced for misfortunes, has likewise declined as of late [11].

High Fructose Corn Syrup Facts

Research affirms that high fructose corn syrup is safe and the same as other essential sweeteners like honey and table sugar. Each of the three sweeteners contains about a similar coordinated proportion of two sugars—glucose and fructose. HFCS has an equal number of calories from table sugar and is equivalent in sweetness. It contains no synthetic or engineered ingredients and it is a natural sweetener. The U.S. Food and Drug Administration conceded HFCS "Generally Recognized as Safe" status for use in food, and endorsed that decision in 1996 after the exhaustive audit. High fructose corn syrup offers various advantages. It keeps food crisp, improves foods flavors, holds moisture in wheat oats, enables keep to breakfast and energy bars moist, empowers heated products to be brown better and keeps ingredients evenly spread in condiments [12, 13].

Glucose syrup containing over 90% glucose is utilized in industrial agitation, but syrups utilized in confectionery production comprise differing measures of glucose, higher oligosaccharides, and maltose, dependent on the grade, and can regularly contain 10 to 43 percent glucose. Glucose syrup is utilized in food to soften texture, prevent crystallization of sugar, include volume, and enhance flavoring. By changing over a portion of the glucose in corn syrup into fructose (utilizing an enzymatic procedure), high quality fructose corn syrup can be developed. Depending upon the strategy for hydrolyze the starch and the degree on which the hydrolysis response has permitted to continue, distinct grades of glucose syrup are manufactured with distinctive uses and characteristics. The syrup is extensively classified by their dextrose equivalent (DE). The hydrolysis procedure continues, the additionally decreasing sugars are manufactured, and higher the DE. Reliant on the method utilized, various compositions of glucose syrups henceforth unique specialized properties can have a similar DE [14, 15].

Glucose Isomerase

The glucose isomerase is employed to change the starch into sugar. In the initial step of this procedure, the plant starch (principally from maize) is "melted" and fragmented into the fundamental glucose, sugars and fructose. In this procedure, amylases and other starch-part enzymes are utilized. In the next step, glucose isomerase changes a part of the glucose into fructose. As glucose is less sweet than fructose, the "sweetness" of the glucose-fructose blend accomplishes nearly a similar sweetness as sugar. Syrups with high fructose content are referred as fructose syrup, isoglucose or HFCS. Especially in the US, these syrups have substituted the beet sugar or traditional cane in cola drinks and lemonade [16, 17].

2. PROCESS SELECTION (METHODOLOGY)

The preliminary raw material in the HFCS production is corn starch, over a series of four foremost preparing steps; the starch is changed over to 42 percent HFCS. The real steps are the change of starch to dextrose feedstock. At that point, preparation of high-quality dextrose feedstock for isomerization. The isomerization of the feedstock to fructose. Secondary, fructose refining, whenever need a fifth stage can be included with further refining of the 42% solution can be utilized to create 55 to 90 percent fructose syrups [8, 18].

2.1. First Enzymatic Step

The primary step changes over the starch slurry to dextrose. The starch slurry is at first a blend of 15-30%amylase and 70-85% amylopectin. A few stages are engaged with the manufacture of dextrose from starch. Firstly, the starch slurry is exposed to a high temperature in which the starch granules breaks and starch progresses toward becoming gelatinized. This gelatinized starch is then diluted by both hydrolysis and high temperature with alpha-amylase. This progression produces liquid, less thick and low molecular weight dextrine products and takes roughly 130 mins [19, 20].

2.2. Second Enzymatic Step

This liquefaction and dextrinization items are like this exposed gradually to hydrolysis procedure by amyloglucosidase to make a glucose syrup. This is suggested to as saccharification, a persistent procedure take up to 75 hours, contingent upon the measure of catalyst present. The final product of the scarification procedure is a 94-96% high dextrose hydrolyzate additionally elegant in stage 2 [21, 22].

In the second step, the dextrose is refined to make a high-quality feedstock essential for the isomerization procedure in step 3. The refining procedure lessens the pollutants, for example, ash and proteins that can impede the proficiency of the isomerization catalyst in step 3. In this procedure, the dextrose is exposed to a progression of filtration ventures to clear the oil and protein. Next, the color of the liquor is removed by a sequence of granulated carbon segments. At that point, the liquor is exposed to ion exchange system which is de-ionized. Finally, the liquor is vaporized to the proper level for the third step then treated with magnesium particles to restrain any calcium particles that may inhibit the isomerase action in step 3 [23].

2.3. Third Enzymatic Step

In the third stage, the dextrose liquor is isomerized to HFCS, is the core procedure. The isomerization organizes changes over the glucose too much sweeter and therefore progressively important fructose yield. The critical advancement that creates this upgraded value possible is the business improvement of immobilized glucose isomerase, a bound enzyme can raised temperatures of the procedure. The expense of the isomerization enzymes is an essential part of the total operating budget in the HFCS procedure. Along these lines, many research exertion has been dedicated to the economics of the enzyme activity and particularly its decay rate [3].

The utilization of immobilized enzyme reactor frameworks (versus cluster responses, with their enzyme) is the typical structure in the industry. In this stage the primary variable is the movement of the enzyme that controls the conversion rate of dextrose to fructose to determine the quality of fructose content in the product. This useful property of the enzyme is adjusted by response conditions. The movement of the enzyme decays with respect to time in an ordinary way. Because of this decay, the reactor framework is structured and worked to limit the fluctuations in action [11].

In the step 4, powder and color are removed from the 42% HFCS over ion exchange and carbon filtration systems. The cation and anion exchange resins which are especially helpful for the removal of color framing bodies and different polluting influences from the fermented polyhydroxy liquor solutions in the present development are the strongly acidic cation and basic anion exchange resins. Among the cation exchange resins of the above kind which can be utilized in the current development are Amberlite IR-112, Aberlite IR-120, and Dowex 50 which are copolymers arranged by responding styrene with different compositions of divinylbenzene and sulfonating the aromatic nucleus [19]. The anion exchange resins which can be utilized in the present innovation are the essential anion exchange resins containing quaternary ammonium groups and which thus can split salts, also, having the absorbing capacity concerning acids. It also include evaporation of the 42% resolution for shipment of solids [14, 17].

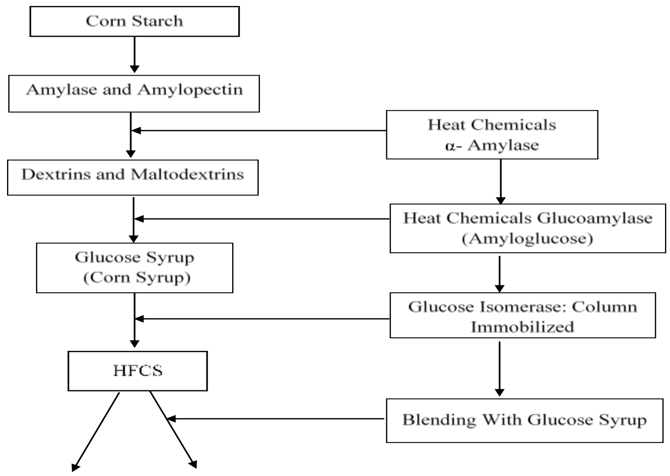

Figure 1: Flow diagram of HFCS production

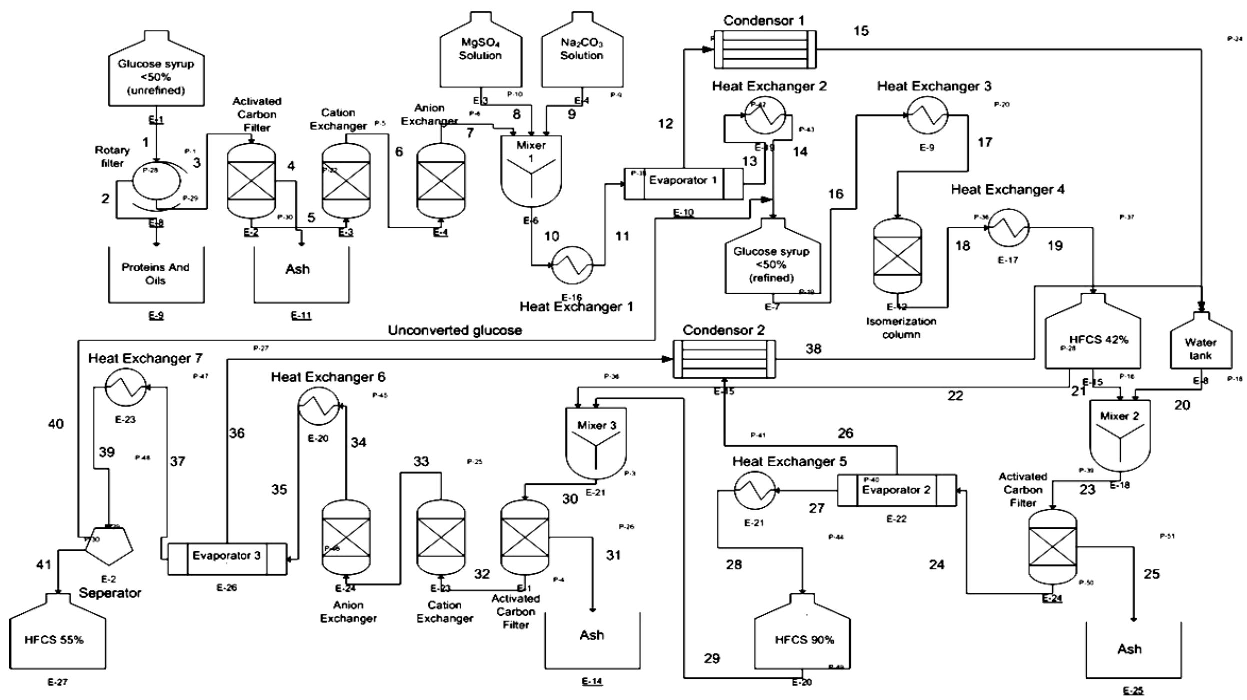

Figure 2: Process flow diagram of HFCS production

Stage 5 includes the specific concentration of the fructose (42%), dextrose (52%) result of step 4 to a higher concentration, 90% fructose product and it's mixing with the first 42% to create different concentrations. Figure 1 shows the flow diagram of HFCS production [7, 8].

Subsequently, fructose favorably forms a complex with cations, whereas dextrose does not. Different decontamination forms use this distinction either through chromatographic fractionation utilizing organic resins or in organizing resins in packed bed frameworks. The instantaneous result of this stage is a Very Enriched Fructose Corn Syrup with a 90% fructose concentration. This syrup can be utilized thus with the 42% HFCS to make a product with various concentrations in the range of 42% and 90% fructose, the most widely recognized being as expressed above as 55% [7]. Figure 2 represents the process flow diagram of HFCS production [10].

3. RESULT & DISCUSSION

Material balance is an application of conservation of mass to the investigation of physical frameworks. It represents the material entering and exodus a system, mass flows can be recognized which may be obscure or hard to quantify deprived of this method. The specific conservation law utilized in the study of the framework relies upon the conditions of the issue; however all spin around mass conservation that issue can't hide or be made suddenly. In this way, mass balances are utilized broadly in engineering and environmental investigations. In environmental monitoring, the term spending computations are utilized to pronounce mass balance equations where they are utilized to assess the observing information. In biology, the theory for metabolic association uses mass and energy balances [19].

3.1. Material Balance

The structure cited for a mass balance is the mass that enters in a framework need by conservation of mass or quit the framework or aggregate inside the frame. Numerically the mass balance for a framework without a chemical response is given as:

$$\text{Input} = \text{Output} + \text{Accumulation}$$

The given equation also for the frameworks with chemical reactions if the terms in the balance equation are taken to allude to total mass, the sum of all the chemical species of the framework.

$$\text{Input} + \text{Generation} = \text{Output} + \text{Accumulation} + \text{Consumption}$$

Without a chemical reaction, the number of chemical species flowing in and out will be the equivalent; this offers to ascend to a condition for every species present in the framework. Moreover, on the off chance that this isn't the situation, at that point, the mass balance equation must be changed to take into consideration for the generation or consumption of each chemical species. Several uses one term from this equation to represent chemical reactions, which will be negative for consumption and positive for a generation. Despite that, the conventional type of equation is composed to represent both a real generation term and a negative consumption term [4, 13].

In general, one term will represent the total balance on the system if the equation is balance can be applied to a singular species and after that the whole procedure, the two terms are vital. This improved equation can be utilized for responsive frameworks, yet for population balances, for example, emerge in particle mechanics issues. In comparison, it simplifies to the prior equation for the situation that the generic term is zero. Without an atomic response, the number of molecules streaming in and out must continue as before, even within the presence of a chemical reaction. The limits of the system must be well defined for a balance formed. Mass balances can be used for physical frameworks at various scales. It can be simplified with the assumption of a steady state, where the aggregation term is zero [5]. The list of equipment with the different stream is shown in Table 2.

Table 2: List of equipment with different stream numbers

Equipment	Stream Numbers	
	Inlet	**Outlet**
Rotary filter	1	2, 3
Activated carbon filter 1	3	4, 5
Mixer 1	7, 8, 9	10
Evaporator 1	11	12, 13
Isomerization column (Reactor)	17	18
Mixer 2	20, 21	23
Activated carbon filter 2	23	24, 25
Evaporator 2	24	26, 27
Mixer 3	22, 29	30
Activated carbon filter 3	30	31, 32
Evaporator 3	35	36, 37
Separator	39	40, 41

3.1.1. *Material Balance on Rotary Filter*

Figure 3 shows the material balance on the rotary filter.

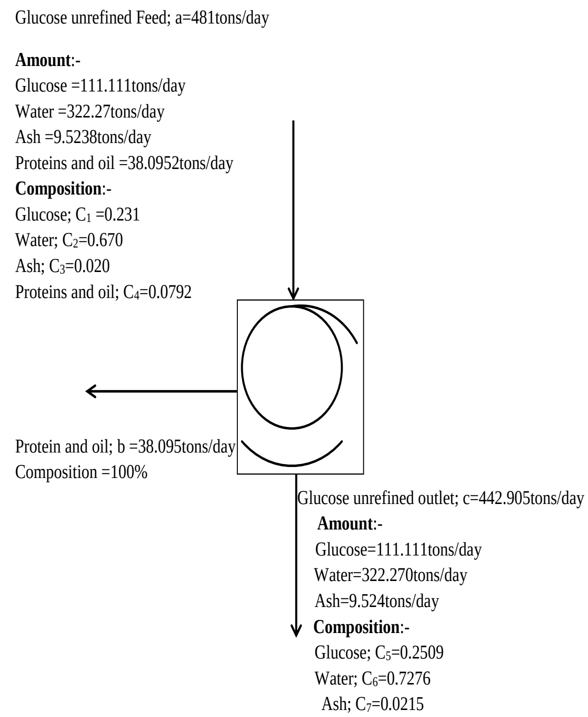

Figure 3: Material balance on the rotary filter

Composition of rotary filler inlet as shown in Table 3.

Table 3: Composition of rotary filler inlet

Glucose unrefined Feed; a =481 tons/day, glucose syrup=0.33	
Composition at Inlet	**Mass Fraction**
Glucose; C_1	0.231
Water; C_2	0.67
Ash; C_3	0.0198
Proteins and oil; C_4	0.0792
Total	1

Overall material balance.

$a=b+c$ (1)

Glucose balance.

$C_1*a=C_5*c$ (2)

Water balance.

$C_2*a=C_6*c$ (3)

Ash balance.

$C_3*a=C_7*c$ (4)

Proteins and oil balance.

$C_4*a=b$ (5)

Equating these equations and amount at the stream of rotary filler as shown in Table 4.

Table 4: Amount at the stream of rotary filler

Amounts at Stream 2	
Proteins and oil; b	38.095 tons/day
Amounts at Stream 3	
Glucose	111.111 tons/day
Water	322.270 tons/day
Ash	9.524 tons/day
Total; c	442.905 tons/day
Composition at Stream 3	
Glucose; C_5	0.2509
Water; C_6	0.7276
Ash; C_7	0.0215
Total	1

3.1.2. Material Balance on Activated Carbon Filter 1

Figure 4 represents a material balance on activated carbon filter 1.

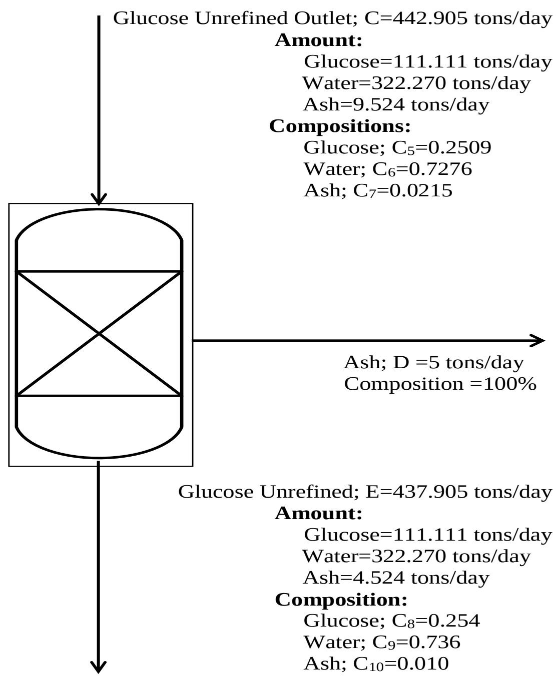

Figure 4: Material balance on activated carbon filter 1

Overall material balance.

$c = d + e$ (6)

Glucose Balance.

$C_5*c = C_8*e$ (7)

Water balance.

$C_6*c = C_9*e$ (8)

Ash balance.

$C_7*e = C_{10}*e + d$ (9)

Equating these equations and amount at the stream of activated carbon filter 1 outlet is calculated in Table 5.

Table 5: Amount at the stream of activated carbon filter 1 outlet

Amounts at Stream 4	
Ash; d	5 tons/day

Amounts at Stream 5	
Glucose	111.111 tons/day
Water	322.270 tons/day
Ash	4.524 tons/day
Total; e	437.905 tons/day
Composition at Stream 5	
Glucose; C_8	0.254
Water; C_9	0.736
Ash; C_{10}	0.010
Total	1

3.1.3. Material Balance on Mixer 1

Figure 5 shows the material balance on mixer 1.

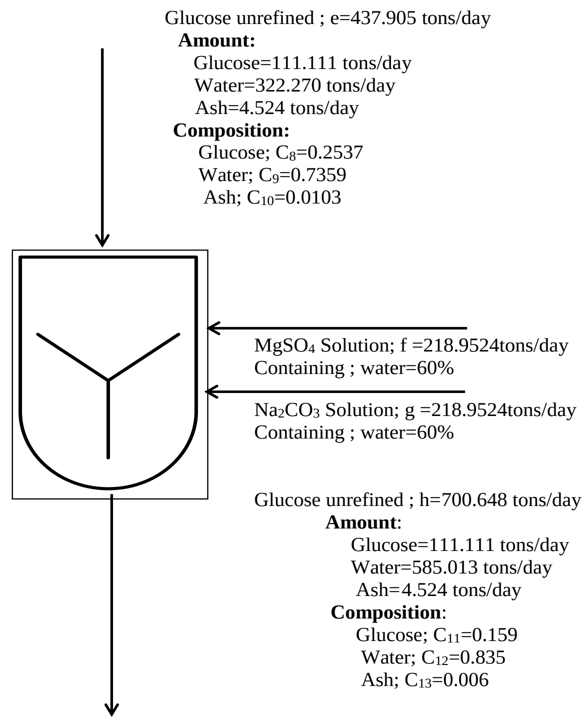

Figure 5: Material balance on mixer 1

$MgSO_4$ solution; f =218.9524

Containing; water=0.6

Na_2CO_3 solution; g =218.9524

Containing; water=0.6

Overall material balance.

$e + f + g = h$ (10)

Glucose balance.

$C_8*e = C_{11}*h$ (11)

Water balance.

$C_9*e + 0.6*f + 0.6*g = C_{12}*h$ (12)

Ash balance.

$C_{10}*e = C_{13}*h$ (13)

Equating these equations and amount at the stream of mixer 1 outlet is calculated in Table 6.

Table 6: Amount at the stream of mixer 1 outlet

Amounts at Stream 6

Glucose	111.111 tons/day
Water	585.013 tons/day
Ash	4.524 tons/day
Total; h	700.648 tons/day
Composition at Stream 6	
Glucose; C_{11}	0.159
Water; C_{12}	0.835
Ash; C_{13}	0.006
Total	1

3.1.4. MATERIAL BALANCE ON EVAPORATOR 1

Figure 6 shows the material balance on evaporator 1.

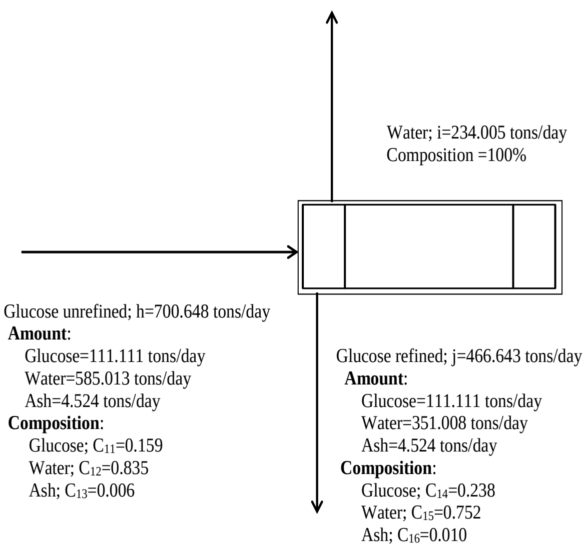

Figure 6: Material balance on evaporator 1

Water evaporated =40

Overall material balance.

$h = i + j$ (14)

Glucose balance.

$C_{11}*h=C_{14}*j$ (15)

Water balance.

$C_{12}*h= i + C_{15}*j$ (16)

Ash balance.

$C_{13}*h = C_{16}*j$ (17)

Equating these equations and amount at the stream of evaporator 1 outlet are calculated in Table 7.

Table 7: Amount at the stream of evaporator 1 outlet

Amount at Stream 7	
water; i=	234.005 tons/day
Amount at Stream 8	
Glucose	111.111 tons/day
Water	351.008 tons/day
Ash	4.524 tons/day
Total; j	466.643 tons/day
Composition at Stream 8	
Glucose; C_{14}	0.238
Water; C_{15}	0.752
Ash; C_{16}	0.010

Total	1

3.1.5. Material Balance on Isomerization Column (Reactor)

Figure 7 represents the material balance on isomerization column 2.

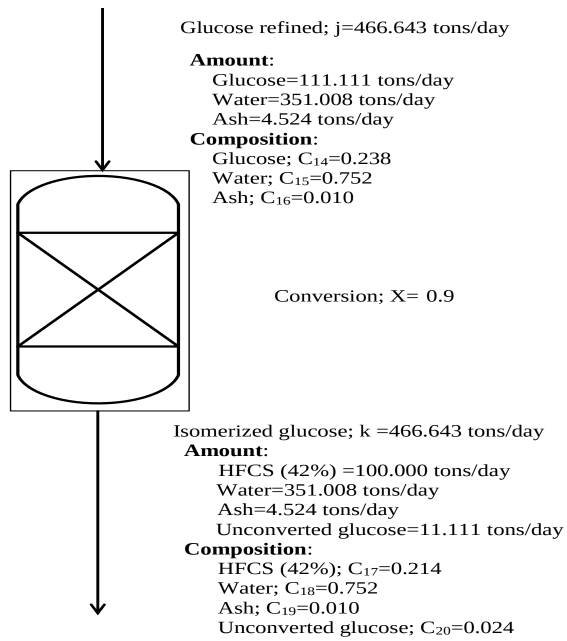

Figure 7: Material balance on isomerization column 2

Conversion; X=0.9

Overall material balance.

$j=k$ (18)

HFCS balance.

$C_{14}*X*j = C_{17}*k$ (19)

Water balance.

$C_{15}*j = C_{18}*k$ (20)

Ash balance.

$C_{16}*j = C_{19}*k$ (21)

Unconverted glucose.

$C_{14}*(1-X)*j = C_{20}*k$ (22)

Equating these equations and amount at stream of reactor outlet is calculated in Table 8.

Table 8: Amount at the stream of the reactor outlet

Amounts at Stream 9	
HFCS (42%)	100.000 tons/day
Water	351.008 tons/day
Ash	4.524 tons/day
Unconverted glucose	11.111 tons/day
Total; k	466.643 tons/day
Composition at Stream 9	
HFCS (42%); C_{17}	0.214
Water; C_{18}	0.752
Ash; C_{19}	0.010
Unconverted glucose; C_{20}	0.024

Total	1

3.1.6. Material Balance on Mixer 2

Figure 8 represents the material balance on mixer 2.

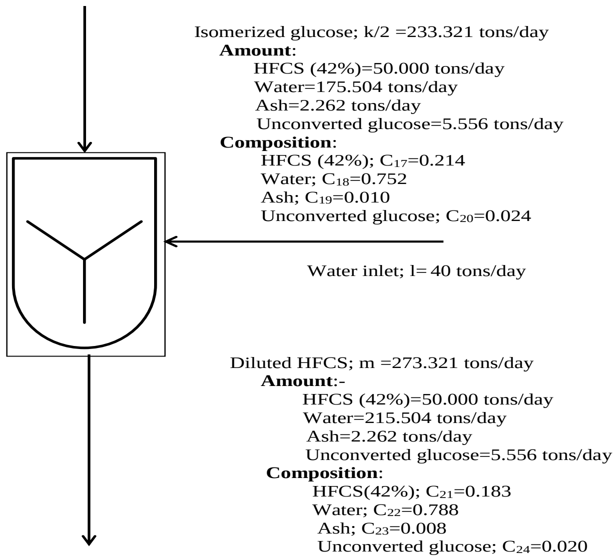

Figure 8: Material balance on mixer 2

Water inlet; l= 40 tons/day

Overall material balance.

$$k = l + m \tag{23}$$

HFCS balance.

$$C_{17}*k/2 = C_{21}*m \tag{24}$$

Water balance.

$$C_{18}*k/2 + l = C_{22}*m \tag{25}$$

Ash balance.

$$C_{19}*k/2 = C_{23}*m \tag{26}$$

Unconverted glucose.

$$C_{20}*k/2 = C_{24}*m \tag{27}$$

Equating these equations and amount at stream of mixer 2 outlet are calculated in Table 9.

Table 9: Amount at stream of mixer 2 outlet

Amounts at Stream 10	
HFCS (42%)	50.000 tons/day
Water	215.504 tons/day
Ash	2.262 tons/day
Unconverted glucose	5.556 tons/day
Total; m	273.321 tons/day
Composition at Stream 10	
HFCS (42%); C_{21}	0.183
Water; C_{22}	0.788
Ash; C_{23}	0.008
Unconverted glucose; C_{24}	0.020
Total	1

3.1.7. Material Balance on Activated Carbon Filter 2

Figure 9 showed the material balance of activated carbon filter 2.

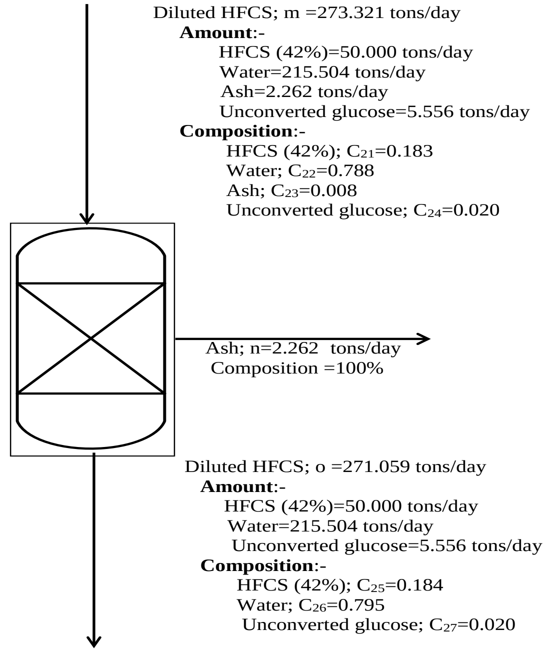

Figure 9: Material balance of activated carbon filter 2

Overall material balance.

$$m = n + o \tag{28}$$

HFCS balance.

$$C_{21}*m = C_{25}*o \tag{29}$$

Water balance.

$$C_{22}*m = C_{26}*o \tag{30}$$

Ash balance.

$$C_{23}*m = n \tag{31}$$

Unconverted glucose.

$$C_{24}*m = C_{27}*o \tag{32}$$

Equating these equations and amount at the stream of activated carbon filter 2 outlet is calculated in Table 10.

Table 10: Amount at the stream of activated carbon filter 2 outlet

Amounts at Stream 11	
Ash; n	2.262 tons/day
Amounts at Stream 12	
HFCS (42%)	50.000 tons/day
Water	215.504 tons/day
Unconverted glucose	5.556 tons/day
Total; o	271.059 tons/day
Composition at Stream 12	
HFCS(42%); C_{25}	0.184
Water; C_{26}	0.795
Unconverted glucose; C_{27}	0.020
Total	1

3.1.8. Material Balance on Evaporator 2

Figure 10 represents the material balance on evaporator 2.

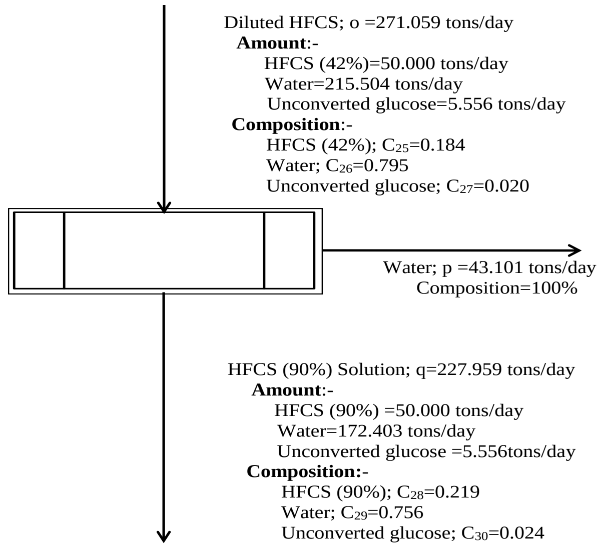

Figure 10: Material balance on evaporator 2

Water evaporated=20%

Overall Material Balance

$o = p + q$ (33)

HFCS Balance

$C_{25}*o = C_{28}*q$ (34)

Water Balance

$C_{26}*o = p + C_{29}*q$ (35)

Unconverted Glucose

$C_{27}*o = C_{30}*q$ (36)

Equating these equations and amount at the stream of evaporator 2 outlets is calculated in Table 11.

Table 11: Amount at the stream of evaporator 2 outlet

Amounts at Stream 13	
Water; p	43.101 tons/day
Amounts at Stream 14	
HFCS (90%)	50.000 tons/day
Water	172.403 tons/day
Unconverted glucose	5.556 tons/day
Total	227.959 tons/day
Composition at Stream 14	
HFCS (90%); C_{28}	0.219
Water; C_{29}	0.756
Unconverted glucose; C_{30}	0.024
Total	1

3.1.9. Material Balance on Mixer 3

Figure 11 shows material balance on mixer 3.

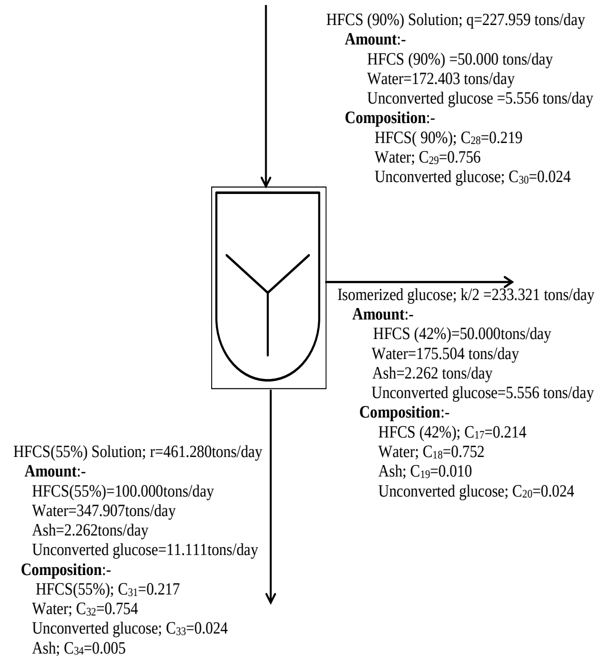

Figure 11: Material balance on mixer 3

Overall material balance.

$k/2 + q = r$ (36)

HFCS balance

$C_{17}*k/2 + C_{28}*q = C_{31}*r$ (37)

Unconverted glucose

$C_{20}*k/2 + C_{30}*q = C_{33}*r$ (38)

Water balance

$C_{18}*k/2 + C_{29}*q = C_{32}*r$ (39)

Ash balance

$C_{19}*k/2 = C_{34}*r$ (40)

Equating these equations and amount at stream of mixer 3 outlet are calculated in Table 12.

Table 12: Amount at the stream of mixer 3 outlet

Amounts at Stream 15	
HFCS (55%)	100.000tons/day
Water	347.907tons/day
Ash	2.262tons/day
Unconverted glucose	11.111tons/day
Total; r	461.280tons/day
Composition at Stream 15	
HFCS (55%); C_{31}	0.217
Water; C_{32}	0.754
Unconverted glucose; C_{33}	0.024
Ash; C_{34}	0.005
Total	1

3.1.10. Material Balance on Activated Carbon Filter 3

Figure 12 represents the material balance on activated carbon filter 3.

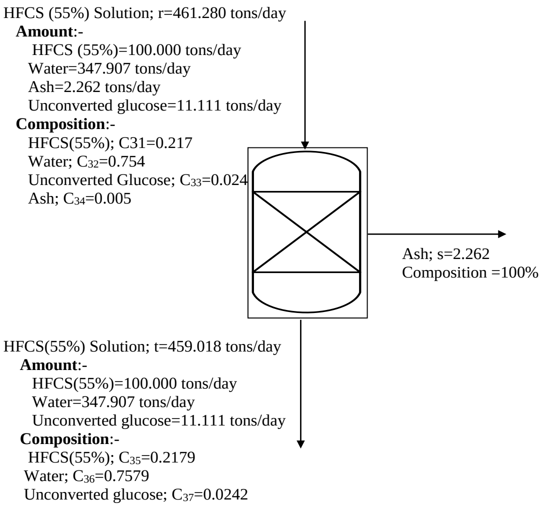

Figure 12: Material balance on activated carbon filter 3

Overall material balance.

$r = s + t$ (41)

HFCS balance.

$C_{31}*r = C_{35}*t$ (42)

Water balance.

$C_{32}*r = C_{36}*t$ (43)

Unconverted glucose.

$C_{33}*r = C_{37}*t$ (44)

Ash balance.

$C_{34}*r = s$ (45)

Equating these equations and amount at the stream of activated carbon filter 3 outlets calculated in Table 13.

Table 13: Amount at the stream of activated carbon filter 3 outlet

Amounts at Stream 16	
Ash; s	2.262 tons/day
Amounts at Stream 17	
HFCS (55%)	100.000 tons/day
Water	347.907 tons/day
Unconverted glucose	11.111 tons/day
Total; t	459.018 tons/day
Composition at Stream 17	
HFCS (55%); C_{35}	0.2179
Water; C_{36}	0.7579
Unconverted glucose; C_{37}	0.0242
Total	1

3.1.11. Material Balance on Evaporator 3

Figure 13 represents the material balance of evaporator 3.

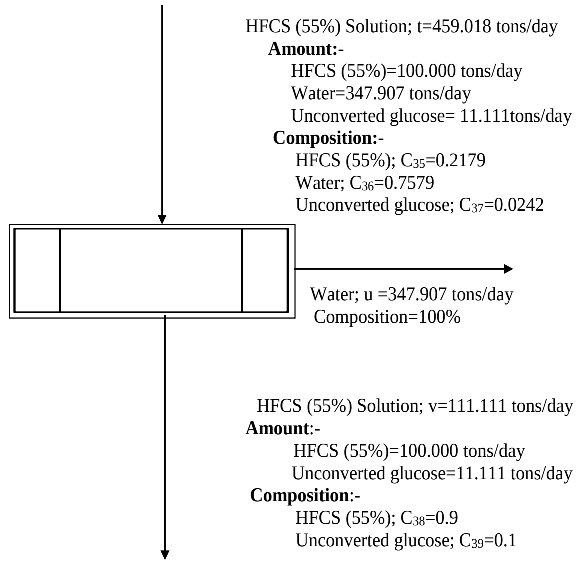

Figure 13: Material balance of evaporator 3

Overall material balance.

$t=u + v$ (46)

HFCS balance.

$C_{35}*t = C_{38}*v$ (47)

Water balance.

$C_{36}*t = u$ (48)

Unconverted glucose.

$C_{37}*t = C_{39}*v$ (49)

Equating these equations and amount at the stream of evaporator 3 outlets calculated in Table 14.

Table 14: Amount at the stream of evaporator 3 outlet

Amounts at Stream 18	
Water; u	347.907 tons/days
Amounts at Stream 19	
HFCS (55%)	100.000 tons/days
Unconverted glucose	11.111 tons/days
Total; v	111.111 tons/days
Composition at Stream 19	
HFCS (55%); C_{38}	0.9
Unconverted glucose; C_{39}	0.1
Total	1

3.1.12. Material Balance on Separator

Figure 14 represents the material balance of separator.

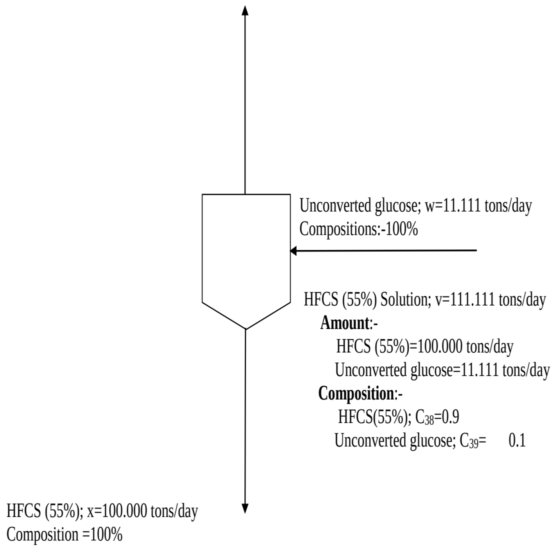

Figure 14: Material balance of separator

Overall material balance.

$v = w + x$ (50)

HFCS balance.

$C_{38}*v= x$ (51)

Unconverted glucose.

$C_{39}*v = w$ (52)

Equating these equations

Amounts at stream 20.

Unconverted glucose; w=11.111 tons/day

Amounts at stream 21.

HFCS (55%); x=100.000 tons/day

3.2. ENERGY BALANCE

The total amount of energy generated in the framework is the sum of the distinctive sorts entering into the framework. Acquisition of anything at steady state is 0 and energy has no exemption. If, have the total time, it is assumed that the system is in steady state, get the equation as [18]:

$E_{in} = E_{out}$ (53)

This equation is the beginning stage for all of the energy balance. The mass stream into or out of the system conveys a specific amount of energy, related to kinetic, internal and potential energy. It is feasible for it to have different sorts of energy too, however, for the time being, assume that these are the main three kinds of energy that are essential. By combining these components, remember that the heat flow into a system and work done on a system are positive, get the equation that is given below [18]:

$$\Sigma(\frac{1}{2}\dot{m}v^2 + \dot{m}gh + \dot{H})_{i,in} - \Sigma(\frac{1}{2}\dot{m}v^2 + \dot{m}gh + \dot{H})_{i,out} + \Sigma\dot{Q}_j + \dot{W}_s = 0 \quad (54)$$

Some basic points are if the framework is shut at a steady state that means the total heat flow is equal to the total work done in magnitude and be inverse. In any case, as indicated by the second law of thermodynamics, it is difficult to change all of the heat flow into work. In an adiabatic framework with no work done, the sum of energy carried by mass flows is equal amid those flowing in and out. Though, it does not infer that the temperature remains the same. A few substances have a higher capacity than others. The conditions in the system changes after some time, at that point, can't use this type of energy balance [8, 16].

3.2.1. Energy Balance on Heat Exchanger

Figures 15 and 16 show the energy balance on heat exchanger 1 and 2, respectively. Heat gained by unrefined glucose = Heat lost by water (assumed).

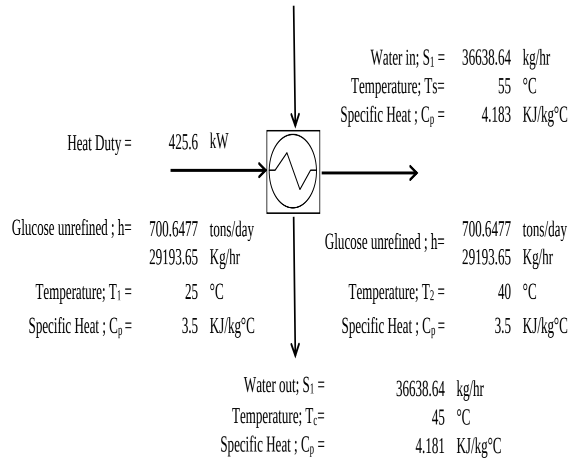

Figure 15: Energy balance of heat exchanger 1

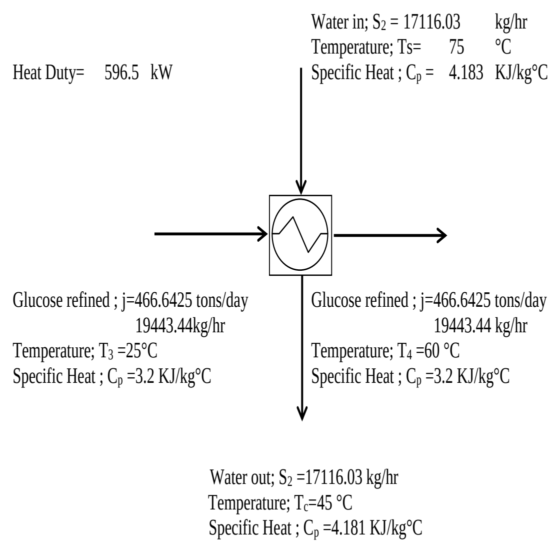

Figure 16: Energy balance of heat exchanger 2

Figure 17 represents energy balance on heat exchanger 3. Heat gained by HFCS (55%) solution = Heat lost by water (assumed).

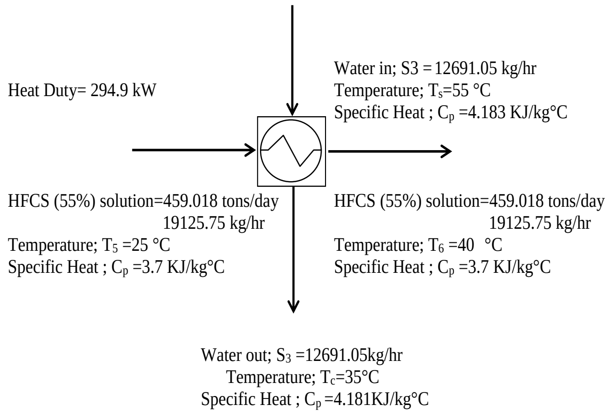

Figure 17: Energy balance of heat exchanger 3

Figure 18 shows energy balance on heat exchanger 4. Heat lost by refined glucose = Heat gained by water (assumed).

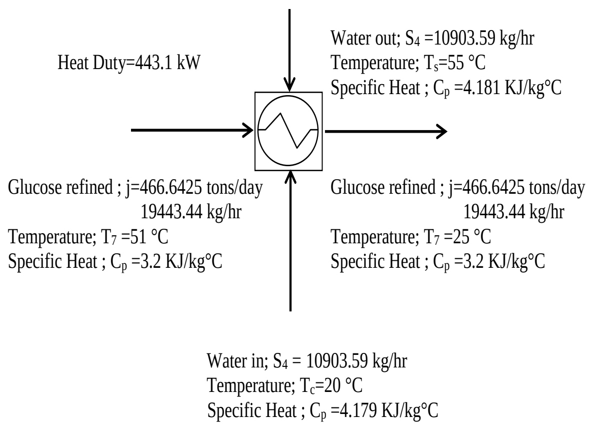

Figure 18: Energy balance of heat exchanger 4

Figure 19 show energy balance on heat exchanger 5. Heat lost by isomerized glucose = Heat gained by water (assumed).

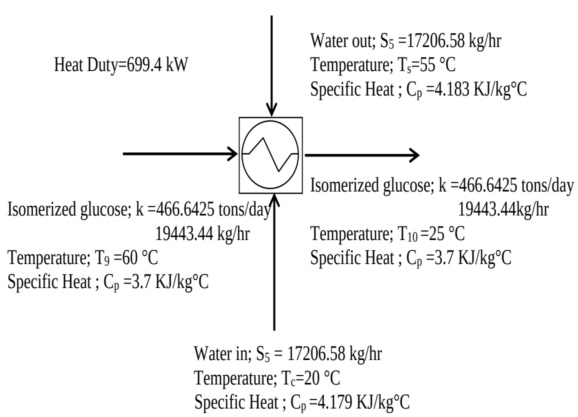

Figure 19: Energy balance of heat exchanger 5

Figure 20 represents energy balance on heat exchanger 6. Heat lost by HFCS (90%) Solution = Heat gained by water (assumed).

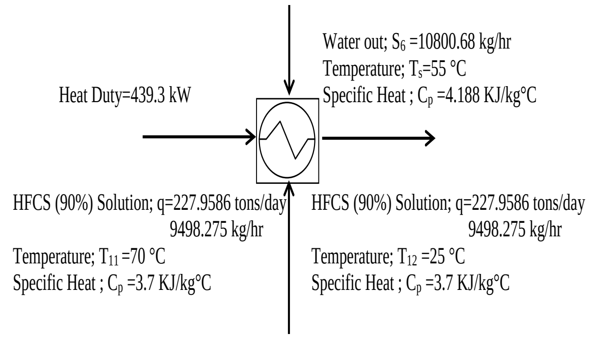

Figure 20: Energy balance of heat exchanger 6

Figure 21 shows energy balance on heat exchanger 7. Heat lost by HFCS (55%) solution = Heat gained by water (assumed).

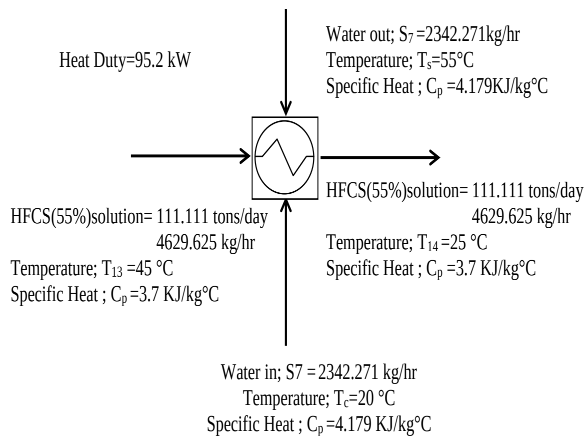

Figure 21: Energy balance of heat exchanger 7

3.2.2. Energy Balance on Condensor 1

Figure 22 shown energy balance on condensor 1.

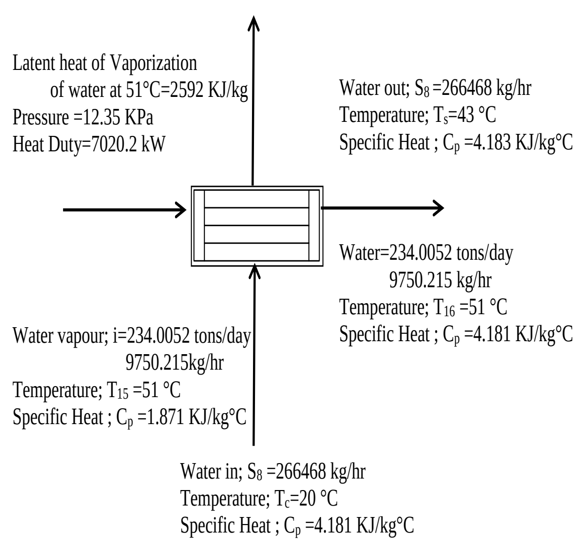

Figure 22: Energy balance on condensor 1

Heat lost by water vapours = Heat gained by water (assumed).

3.2.3. Energy Balance on Condensor 2

Figure 23 represents energy balance on condenser 2

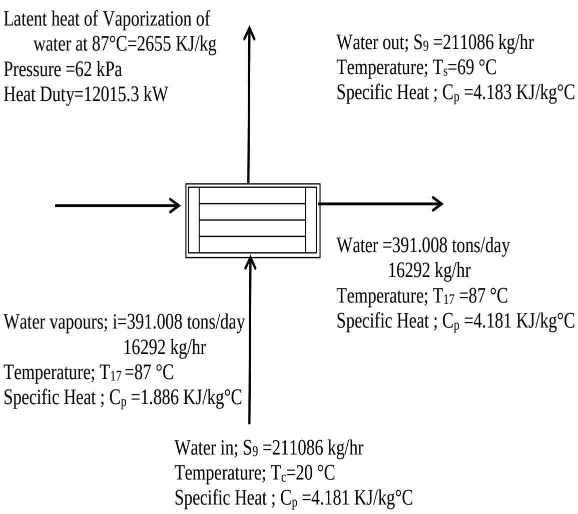

Figure23: Energy balance on condenser 2

Heat lost by water vapours = Heat gained by cold water (assumed). Table 15 presents heat loss and gain by condenser 2.

Table 15: Heat loss and gain by condenser 2

Parameters	ΔQ (KJ/hr)	ΔQ (KW)	'm' or 'S' (kg/hr)	
Heat lost by water = Heat gained by				
Unrefined glucose	1532228	425.62	36638.64	S_1
Refined glucose	2147378	596.5	17116.03	S_2
HFCS (55%)	1061479	294.9	12691.05	S_3
Heat gained by the water = Heat lost by				
Unrefined glucose	1595195	443.1	10903.59	S_4
Refined glucose	2517925	699.4	17206.58	S_5
HFCS (90%)	1581463	439.3	10800.68	S_6
HFCS (55%)	342592.3	95.2	2342.271	S_7
Water vapours	25272556	7020.2	266520.2	S_8
Heat gained by cold water = Heat lost by				
Water vapours	43255230	12015.3	211085.6	S_9

3.2.4. Energy Balance on Mixer 1

Figure 24 represents of energy balance on mixer 1.

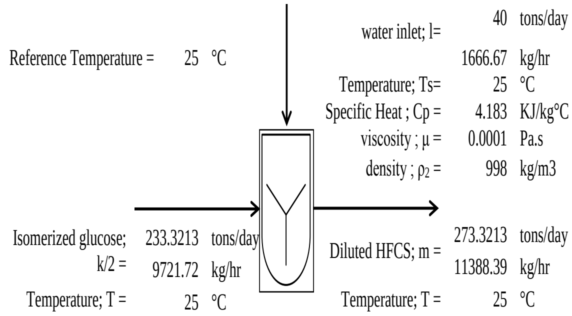

Figure 24: Energy balance on mixer 1

The specification of the energy balance of mixer 1 is calculated in Table 16.

Cooling Water Jacket

Figure 25 shows the energy balance of the cooling water jacket

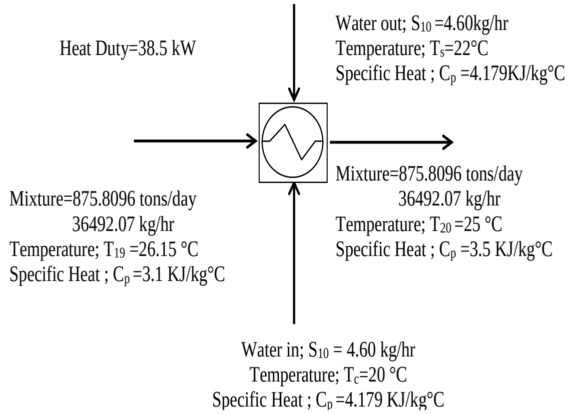

Figure 25: Energy balance of cooling water jacket

Table 16: Enthalpies on mixer 1

Parameter	Operating condition	
Enthalpies	KJ/mol	
HFCS (42%) Water Ash Glucose	-1271 -285.83 0 -1271	
Isomerised glucose; k/2		
Amount	tons/day	Kmol/hr
HFCS (42%) Water Ash Unconverted glucose Total	50.000 175.504 2.262 5.556	11.564 406.259 7.854 1.285 **426.96**
Compositions		
HFCS(42%); C_{17} Water; C_{18} Ash; C_{19} Unconverted glucose; C_{20}	0.214 0.752 0.010 0.024	
Water inlet; l	40 tons/day	92.593 Kmol/hr
Total inlet moles	519.554 Kmol/hr	
Isomerized glucose; x_1 Water; x_2	0.822 0.178	
Inlet Enthalpy		
Isomerised glucose	-310.219 KJ/mol	

Water Diluted HFCS; m	-285.83 KJ/mol 273.321 tons/day	
Amounts	tons/day	Kmol/hr
HFCS (42%) Water Ash Unconverted glucose Total	50.000 215.504 2.262 5.556	11.564 498.852 7.854 1.285 **519.55**
Compositions:- Total = HFCS(42%); C_{21} Water; C_{22} Ash; C_{23} Unconverted glucose; C_{24}	0.183 0.788 0.008 0.020	
Heat at Inlet; ΔQ	-44.14 KW	
Heat at Outlet; ΔQ	-44.14 KW	
Impeller Design		
Number of blades Type of blades Diameter of the turbine Position of the turbine (above the bottom of the tank) Width of blades Turbine impeller speed	6 Flat 0.67 m 0.67 m 0.134 m 120rpm = 2rps	
Turbulent flow; Re	9701600	
Power ; P	4.496 KW	
The time required to fill the mixer; t_T	0.0050 hr	

Table 17 represents heat loss and gain of cooling water jacket.

Table 17: Heat loss and gain of the cooling water jacket

Parameter	Condition
Heat lost by mixture; T_{19}	26.15 °C
Heat gained by water in; S_{10}	4.60 kg/hr

3.2.5. Energy Balance on Mixer 2

Figure 26 shown energy balance of mixer 2.

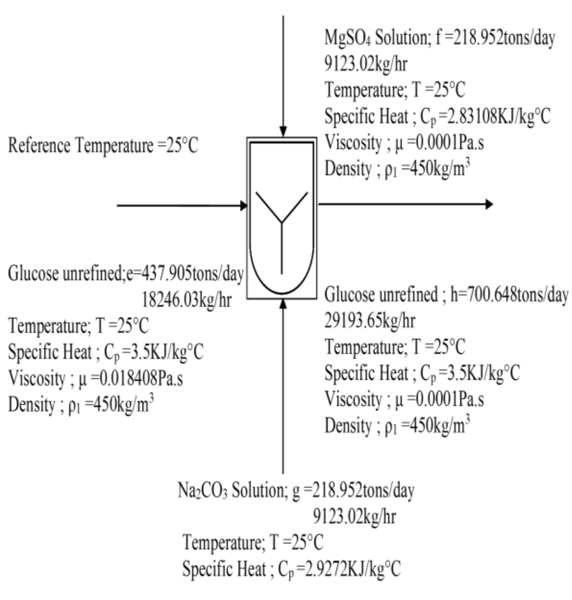

Figure 26: Energy balance of mixer 2

Table 18 represents enthalpies and composition of mixer 2

Table 18: Enthalpies and composition of mixer 2

Parameter	Operating condition	
Enthalpies	KJ/mol	
HFCS Water Ash Glucose Na_2CO_3 $MgSO_4$	-1271 -285.83 0 -1271 -1430.1 -1284.9	
Glucose unrefined ; e	437.905 tons/day	
Amounts	tons/day	Kmol/hr
Glucose Water Ash Total	111.111 322.270 4.524	25.697 745.995 15.708 **787.400**
Compositions:- Glucose; C_8 Water; C_9 Ash; C_{10}	0.2537 0.7359 0.0103	
$MgSO_4$ Solution; f	218.9524 tons/day	
Amounts	tons/day	Kmol/hr
$MgSO_4$ Water Total	87.581 131.371	30.410 304.101 **334.511**
Compositions:- $MgSO_4$ Water; C_9	0.4000 0.6000	
Na_2CO_3 Solution; g	218.9524 tons/day	
Amounts	tons/day	Kmol/hr
Na_2CO_3 Water Total	87.581 131.371	34.426 304.101 **338.527**
Compositions:- $MgSO_4$ Water; C_9	0.4000 0.6000	
Total inlet Moles	1460.438 Kmol/hr	
Mole Fractions: Glucose unrefined; x_1 $MgSO_4$ solution; x_2 Na_2CO_3 solution ;x_3	0.539 0.229 0.232	
Inlet Enthalpy	KJ/mol	
Glucose unrefined; h_1 $MgSO_4$ solution ;h_2 Na_2CO_3 solution ;h_3	-41.4799 -116.81 -145.43	
Glucose unrefined; h	700.648 tons/day	
Amounts	tons/day	Kmol/hr
Glucose Water Ash Total	111.111 585.013 4.524	25.697 1354.196 15.708 **1395.601**
Compositions:- Glucose; C_{11} Water; C_{12} Ash; C_{13}	0.159 0.835 0.006	
Total outlet Moles	1460.438 Kmol/hr	
Outlet Enthalpies HFCS (55%) solution; h_m	-300.75 KJ/mol	
Heat of mixing; ΔH(mix)	-217.923 KJ/mol	
Heat at inlet; ΔQ	-120853 KJ/hr	-33.57 KW
Heat at outlet; ΔQ	-121071 KJ/hr	-33.63 KW
Impeller Design		
Fluid with moderate viscosity Type of impeller Number of blades	0.006202705 Pa.s Disk Turbine 6	

Type of blades	Flat	
The diameter of the turbine	0.67 m	
Position of the turbine (above the bottom of the tank)	0.67 m	
Width of blades	0.134 m	
Turbine impeller speed	90 rpm =1.5 rps	
Turbulent flow; Re	72911.74	
Power ; P	1179 W	1.179 KW
Mixing time factor; n t_T	24 s	

Cooling Water Jacket

Figure 27 shown energy balance of the cooling water jacket.

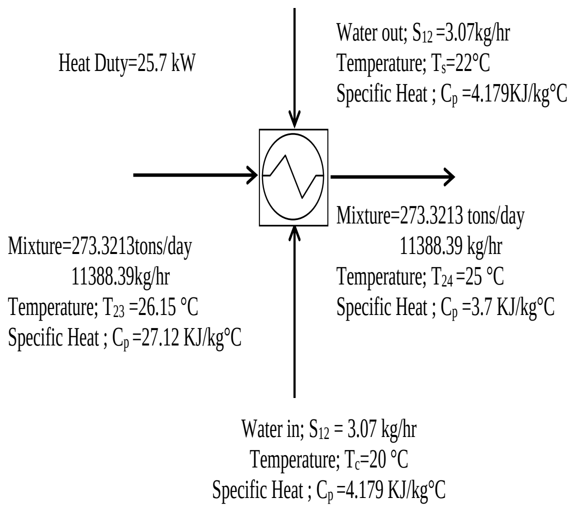

Figure 27: Energy balance of cooling water jacket

Table 19 represents heat loss and gains in cooling water jacket.

Table 19: Heat loss and gain in the cooling water jacket

Parameter	Condition
Heat lost by mixture; T_{23}	27.12 °C
Heat gained by water m; S_{12}	3.07 kg/hr

3.2.6. Energy Balance on Mixer 3

Figure 28 shown energy balance of mixer 3.

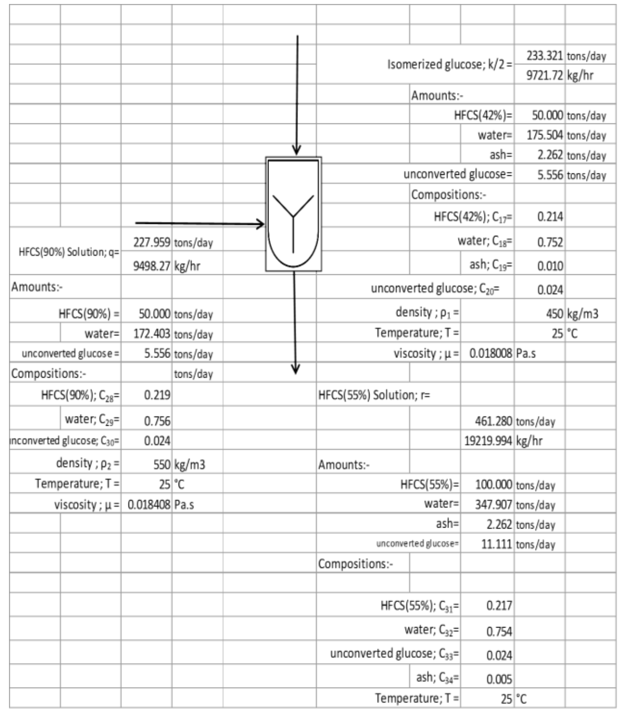

Figure 28: Energy balance of mixer 3

Table 20 represents calculated enthalpy and amount on mixer 3

Table 20: Enthalpy and amount on mixer 3

Parameter	Operating condition	
Enthalpies	KJ/mol	
HFCS	-1271	
Water	-285.83	
Ash	0	
Glucose	-1271	
Na_2CO_3	-1430.1	
$MgSO_4$	-1284.9	
HFCS (90%) solution; q	227.959 tons/day	
Amounts:	tons/day	Kmol/hr
HFCS (90%)	50.000	11.564
Water	172.403	399.081
Unconverted glucose	5.556	1.285
Total		411.930
Compositions:-		
HFCS(90%); C_{28}	0.219	
water; C_{29}	0.756	
unconverted glucose; C_{30}	0.024	
Isomerized glucose; k/2	233.321 tons/day	
Amounts:	tons/day	Kmol/hr
HFCS (42%)	50.000	11.564
Water	175.504	406.259
Ash	2.262	7.854
Unconverted glucose	5.556	1.285
Total		**426.96**
Compositions:-		
HFCS (42%); C_{17}	0.214	
Water; C_{18}	0.752	
Ash; C_{19}	0.010	
Unconverted glucose; C_{20}	0.024	
Total inlet moles	838.891Kmol/hr	
Mole fractions:		
Isomerized glucose; x_1	0.509	
HFCS (90%) solution ;x_2	0.491	

Inlet Enthalpy :		
Isomerized glucose; h_1	-310.219 KJ/mol	
HFCS (90%) solution ; h_2	-316.559 KJ/mol	
HFCS (55%) solution; r	461.280 tons/day	
Amounts:	tons/day	Kmol/hr
HFCS (55%)	100.000	23.128
Water	347.907	805.340
Ash	2.262	7.854
Unconverted glucose	11.111	2.570
Total		**836.322**
Compositions:-		
HFCS(55%); C_{31}	0.217	
Water; C_{32}	0.754	
Unconverted glucose; C_{33}	0.024	
Ash; C_{34}	0.005	
Outlet Enthalpies		
HFCS (55%) solution ; h_m	-314.29 KJ/mol	
Heat of mixing; ΔH (mix)	-0.96276 KJ/mol	
Heat at inlet; ΔQ	-262852 KJ/hr	-73.014 KW
Heat at outlet; ΔQ	-263659 KJ/hr	-73.24 KW
Impeller Design		
Fluid with moderate viscosity	0.01820806 Pa.s	
Type of impeller Turbine	Disk	
Number of blades	6	
Type of blades	Flat	
Diameter of the turbine	0.67 m	
Position of the turbine (above the bottom of the tank)	0.67 m	
Width of blades	0.134 m	
Turbine impeller speed	90 rpm = 1.5 rps	
Turbulent flow; Re	27597.67	
Power ; P	1310 W	1.310 KW
The time required to fill the mixer; t_T	24 s	

Cooling Water Jacket

Figure 29 represents the energy balance of cooling water jacket system.

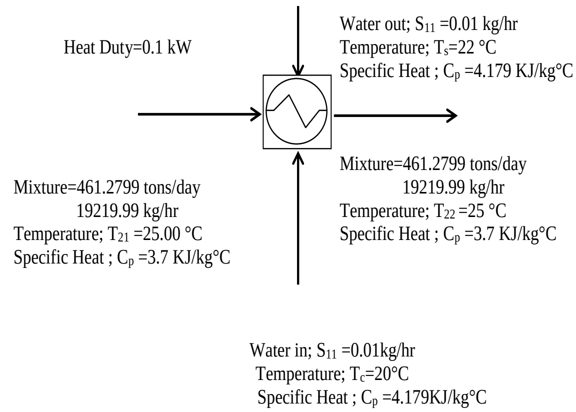

Figure 29: Energy balance of cooling water jacket

Table 21 shown heat loss and gain in cooling water jacket system.

Table 21: Heat loss and gain in the cooling water jacket

Parameter	Operating condition
Heat lost by Mixture	0.01 kg/hr
T_{21}	25.00 °C
Heat gained by Water	
m=S_{11}	0.01 kg/hr

3.2.7. Energy Balance on Evaporator 1

Figure 30 showed the energy balance of evaporator 1

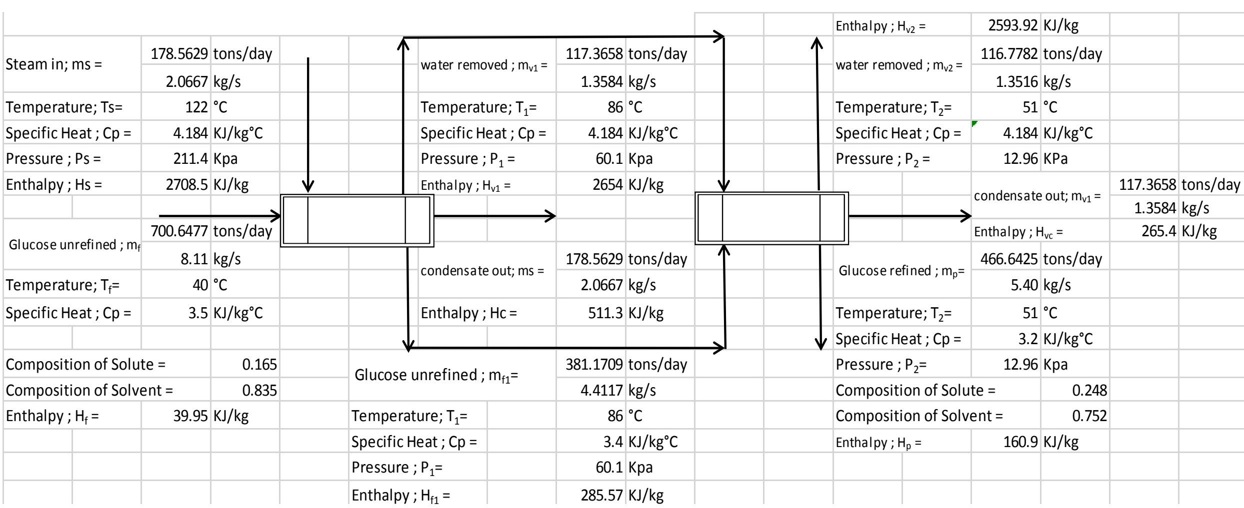

Figure 30: Energy balance of evaporator 1

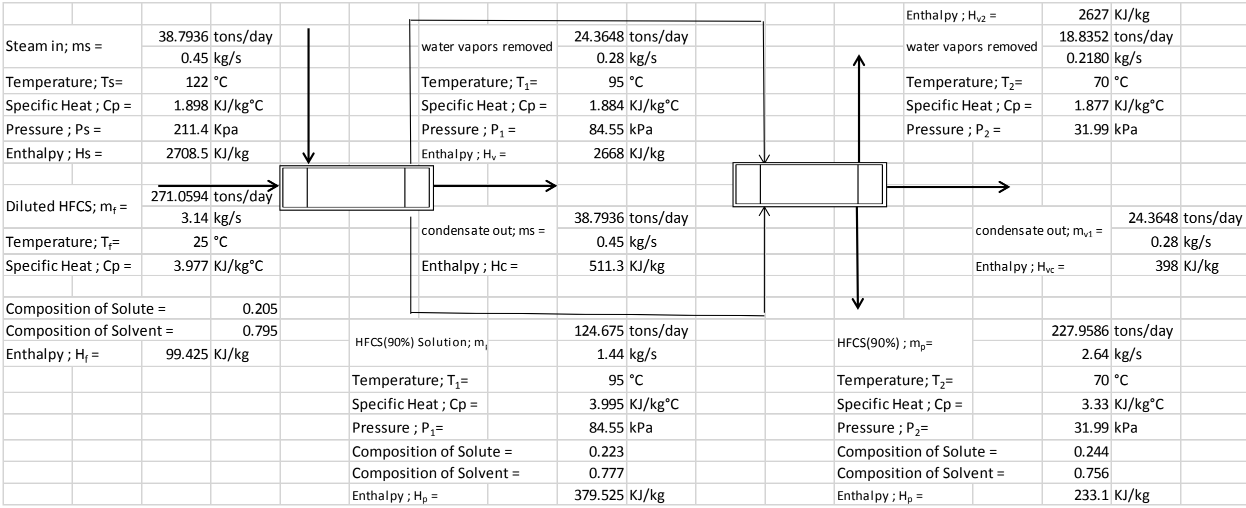

Figure 31: Energy balance of evaporator 2

The parameters of energy balance on evaporator 1 to applying the material and energy balance are;

Applying overall material balance

$m_f = mv_1 + mv_2 + m_p$

$8.109348 = mv_1 + mv_2 + 5.40$

$mv_1 + mv_2 = 2.71$

Applying energy balance

First Effect :

$m_f H_f + m_s H_s = mv_1 + m_{f1} H_{f1} + m_s H_c$

2654 mv1 + 285.57 mf1 - 2197.2 ms = 323.9945

Second Effect :

$m_{f1} H_{f1} + mv_1 Hv_1 = m_p H_p + mv_2 Hv_2 + mv_1 H_{vc}$

$2294\ mv_1 - 2593.92\ mv_2 + 285.57\ m_{f1} = 868.86$

Assumptions

Overall heat transfer co- efficient in first effect

$U_1 = 1.7 KW/m^2.K$

Overall heat transfer co- efficient in second effect

$U_2 = 1.2 KW/m^2.K$

Area of First Effect = Area of the second Effect

$A_1 = A_2$

$54.62\ mv_1 - 35.9\ m_s = 0$

Solving equations

Water removed ; mv_1 = 1.3584 kg/s

Water removed ; mv_2 = 1.3516 kg/s

Steam in; m_s = 2.0667 kg/s

Glucose unrefined ; m_{f1}= 4.4117 kg/s

Steam Economy = 1.311

Heat Duty

First Effect

Q_1 = 4540.95 KW

Second Effect

Q_2 = 3244.67 KW

Total Heat Duty = 7785.63 KW

Areas

First Effect

$A_1 = 74.20\ m^2$

Second Effect :

Q_2 = 3116.34 KW

So heat loss in second effect =128.33 KW

3.2.8. Energy Balance on Evaporator 2

Figure 31 showed the energy balance of evaporator 2. The parameters of material and energy balance on applying evaporator 2 are:

Applying overall material balance

$m_f = mv_1 + mv_2 + m_p$

$3.14 = mv_1 + mv_2 + 2.64$

$mv_1 + mv_2 = 0.50$

Applying energy balance

First Effect :

$m_f H_f + m_s H_s = mv_1 + m_{f1} H_{f1} + m_s H_c$

$2668\ m_{v1} + 379.52\ m_{f1} - 2197.2\ m_s = 312.1945$

Second Effect :

$m_{f1} H_{f1} + mv_1 H_{v1} = m_p H_p + mv_2 H_{v2} + mv_1 H_{vc}$

$4897\ mv_1 + 379.525\ m_{f1} = 1928.884$

Assumptions

Overall heat transfer co- efficient in first effect

$U_1 = 1.7\ KW/m^2.K$

Overall heat transfer co- efficient in second effect

$U_2 = 1.2\ KW/m^2.K$

Area of First Effect = Area of second Effect

$A_1 = A_2$

$76.33\ mv_1 - 47.87\ m_s = 0$

Solving equations

Water removed ; mv_1 = 0.282 kg/s

Water removed ; mv_2 = 0.2180 kg/s

Steam in; m_s = 0.449 kg/s

Glucose unrefined ; m_{f1}=1.443 kg/s

Steam Economy

S.E = 1.114

Heat Duty

First Effect :

$Q_1 = m_s (H_s - H_c)$

$Q_1 = 986.54$ KW

Second Effect :

$Q_2 = mv_1 (H_{v1} - H_{vc})$

$Q_2 = 640.14$ KW

Total Heat Duty = $Q_1 + Q_2$

Total Heat Duty = 1626.68 KW

Areas

First Effect :

$Q_1 = U_1 A_1 (T_s - T_1)$

$A_1 = 21.49 \ m^2$

Second Effect :

$Q_2 = U_2 A_2 (T_1 - T_2)$

$Q_2 = 644.80$ KW

So heat loss in Second Effect = 4.66 KW

3.2.9. Energy Balance on Reactor

Figure 32 represents the energy balance of the reactor.

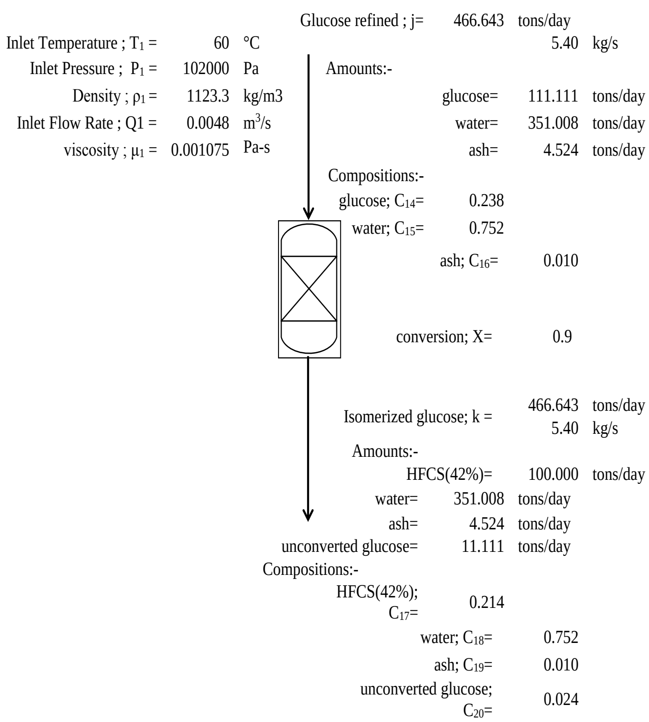

Figure 32: Energy balance of reactor

The energy balance equation for steady state flow process is;

$Q + W_s + \sum F_i H_i \text{ (in)} - \sum F_i H_i \text{ (out)} = 0$

For PBR; $W_s = 0$

Solving the above equation gives

$Q = -FA_o \sum \theta i (H_{io} - H_i) + \Delta HR (T) FA_o X$

Assumptions

1) Isothermal Operation

2) $H_{io} = H_i$

So above equation become as

$Q = \Delta HR (T) FA_o X$

since, $H_i (T) = H_i° (TR) + \int Cp_i \, dT$

Intgral Limits

lower = TR

Upper = T

Calculating inlet

H_i (T) = -1247.7 KJ/mol (For Glucose)

H_i (T) = -283.3 KJ/mol (For Water)

H_i (T) = 0.298 KJ/mol (For Ash)

Calculating outlet

H_i (T) = -1257.53 KJ/mol (For HFCS 42%)

H_i (T) = -283.2 KJ/mol (For Water)

H_i (T) = 0.298 KJ/mol (For Ash)

H_i (T) = -1247.7 KJ/mol (For Unconverted Glucose)

Now,

$\Delta HR (T) = \sum H \text{ (product)} - \sum H \text{ (reactant)}$

$\Delta HR (T) = -0.17041$ KJ/mol

So,

Q = -1.09475KW

Now,

$Q = mcp\Delta T$

$\Delta T = 6.43$ °C

Cooling Water Jacket of Reactor

Figure 33 shown energy balance on the cooling jacket of the reactor system.

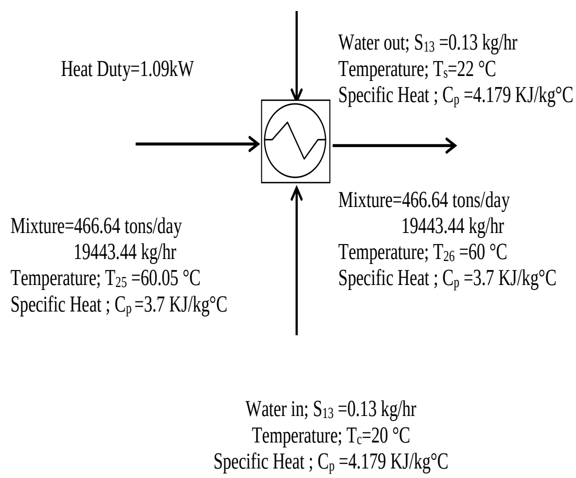

Figure 33: Energy balance on the cooling jacket of the reactor

Table 22 represents heat loss and gain of cooling water jacket reactor system.

Table 22: Heat loss and gain of cooling water jacket reactor

Parameters	Operating Condition
Heat lost by Mixture	
T_{25}	60.05 °C
Heat gained by Water	
$m=S_{13}$	0.13 kg/hr

CONCLUSION

High-fructose corn syrup is a fructose-glucose liquid sweetener proposed as a substitute to sucrose, honey, and concentrated fruit juice. As compare to other sweeteners, HFCS has generally economical. The sweetness profile of HFCS improves numerous fruits, citrus and spice flavors in refreshments, bakery fillings and dairy items. HFCS was widely incorporated by food formulators, and mostly as a substitute for sucrose. This was principally because of its sweetness comparable with sweetness of sucrose, improved functionality, stability and ease of use. The starch is converted to HFCS 42%, through four major treating stages. A fifth stage can be added for the refining of fructose product in which extra refining of the 42% HFCS solution can be used to produce high quality fructose syrups of 55% and 90%.

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REFERENCES

[1] Rippe, J.M. and Angelopoulos, T.J., "Sucrose, high-fructose corn syrup, and fructose, their metabolism and potential health effects: what do we really know?", *Advanced Nutrition*, **4** (2): 236-245 (2013).

[2] Goran, M.I., Ulijaszek, S.J. and Ventura, E.E., "High fructose corn syrup and diabetes prevalence: a global perspective", *Glob Public Health*, **8** (1): 55-64 (2013).

[3] Johnson, R. and Padmaja, G., "Comparative Studies on the Production of Glucose and High Fructose Syrup from Tuber Starches", *International Research Journal of Biological Sciences*, **2** (10): 68-75 (2013).

[4] Jia, D.X., Zhou, L. and Zheng, Y.G., "Properties of a novel thermostable glucose isomerase mined from Thermus oshimai and its application to the preparation of high fructose corn syrup", *Enzyme and Microbial Technology*, **99** 1-8 (2017).

[5] Patel, A.K., Singhania, R.R. and Pandey, A., "Novel enzymatic processes applied to the food industry", *Current Opinion in Food Science*, **7** 64-72 (2016).

[6] Grembecka, M., "Sugar alcohols—their role in the modern world of sweeteners: a review", *European Food Research and Technology*, **241** (1): 1-14 (2015).

[7] Jin, L.Q., Xu, Q., Liu, Z.Q., Jia, D.X., Liao, C.J., Chen, D.S. and Zheng, Y.G., "Immobilization of Recombinant Glucose Isomerase for Efficient Production of High Fructose Corn Syrup", *Applied Biochemical Biotechnology*, **183** (1): 293-306 (2017).

[8] Wang, Z., Sharma, V., Dien, B.S. and Singh, V., "High-conversion hydrolysates and corn sweetener production in dry-grind corn process", *Cereal Chemistry*, **95** (2): 302-311 (2018).

[9] Franssen, M.C., Steunenberg, P., Scott, E.L., Zuilhof, H. and Sanders, J.P., "Immobilised enzymes in biorenewables production", *Chemical Society Review*, **42** (15): 6491-6533 (2013).

[10] Shakoor, S., Singh, G. and Singh, M., "Glucose Isomerase Production and Its Application In Various Field", *International Journal of Scientific Research in Science and Technology*, **4** (5): 690-699 (2018).

[11] Ramachandran, V., Pujari, N., Matey, T. and Kulkarni, S., "Enzymatic Hydrolysis for Glucose-A Review", *International Journal of Science, Engineering and Technology Research*, **2** (10): 1937-1942 (2013).

[12] Payne, A.N., Chassard, C. and Lacroix, C., "Gut microbial adaptation to dietary consumption of fructose, artificial sweeteners and sugar alcohols: implications for host-microbe interactions contributing to obesity", *Obesity Reviews*, **13** (9): 799-809 (2012).

[13] Liu, C., Carraher, J.M., Swedberg, J.L., Herndon, C.R., Fleitman, C.N. and Tessonnier, J.-P., "Selective Base-Catalyzed Isomerization of Glucose to Fructose", *ACS Catalysis*, **4** (12): 4295-4298 (2014).

[14] Gensberger, S., Mittelmaier, S., Glomb, M.A. and Pischetsrieder, M., "Identification and quantification of six major alpha-dicarbonyl process contaminants in high-fructose corn syrup", *Anal Bioanal Chem*, **403** (10): 2923-2931 (2012).

[15] Hii, S.L., Tan, J.S., Ling, T.C. and Ariff, A.B., "Pullulanase: role in starch hydrolysis and potential industrial applications", *Enzyme Research*, **2012** (1): 1-14 (2012).

[16] Kwan, T.H., Ong, K.L., Haque, M.A., Kulkarni, S. and Lin, C.S.K., "Biorefinery of food and beverage waste valorisation for sugar syrups production: Techno-economic assessment", *Process Safety and Environmental Protection*, **121** 194-208 (2019).

[17] Pérez Nebreda, A., Russo, V., Di Serio, M., Eränen, K., Murzin, D.Y., Salmi, T. and Grénman, H., "High purity fructose from inulin with heterogeneous catalysis - from batch to continuous operation", *Journal of Chemical Technology & Biotechnology*, **94** (2): 418-425 (2019).

[18] Moehlenbrock, M.J. and Minteer, S.D., "Introduction to the field of enzyme immobilization and stabilization", *Methods in Molecular Biology*, **679** 1-7 (2011).

[19] Moliner, M., "State of the art of Lewis acid-containing zeolites: lessons from fine chemistry to new biomass transformation processes", *Dalton Transactions*, **43** (11): 4197-4208 (2014).

[20] Kaushik, N., Biswas, S. and Singh, J., "Biocatalysis and Biotransformation Processes – An Insight", *The Scitech Journal*, **1** (8): 15-22 (2014).

[21] Singh, I., Langyan, S. and Yadava, P., "Sweet Corn and Corn-Based Sweeteners", *Sugar Technology*, **16** (2): 144-149 (2014).

[22] Olivares-Pérez, A., Mejias-Brizuela, N.Y., Grande-Grande, A. and Fuentes-Tapia, I., "Corn syrup holograms", *Optik*, **123** (5): 447-450 (2012).

[23] Yu, Z., Lowndes, J. and Rippe, J., "High-fructose corn syrup and sucrose have equivalent effects on energy-regulating hormones at normal human consumption levels", *Nutrition Research*, **33** (12): 1043-1052 (2013).