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Effects of Input Variables on the Conversion of 5 Ton/h Processed Tomato Juice in a Triple-Effect Evaporator

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Authors' contributions

This work was carried out in collaboration between all authors. Author MMO did and managed the literature searches, designed the study, wrote the protocol and the draft of the manuscript. Author FPI wrote and run the programme for the design. Author BAO supervised the study. All authors read and approved the final manuscript.

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Short Research Article

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ABSTRACT

Tomato is grown in many regions of the world; and processed tomato products account for 80% of total tomato consumption. A worldwide tomato processing industry has since evolved with a range of technologies which are able to convert tomatoes into products such as paste, sauces and ketchup. Tomato concentrate production can be classified as either Hot Break (HB) process or Cold Break (CB) process. CB process involves chopping the fresh tomato suitable for processing at lower temperatures, ranging from 65 to 75°C, resulting in a less viscous, but slightly better flavoured paste which is mainly used for triple concentrate paste, packed for domestic use. The heated tomato pulp is then conveyed via a special pump to an extraction unit. Two products, the refined juice for concentrate and the waste for disposal come out of the extraction unit. The yield from extractor (about 95%) varies according to the variety of tomatoes treated, pulp's temperature, type of sieve fitted, the rotation speed, and shape of the rotor on each operating stations. The

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refined juice is collected and constantly feed to an evaporator from where it passes through different effect(s) where its concentration level is gradually increased until the required concentration is obtained.
This study is aimed at using Matrix Laboratory (MATLAB®) to model a triple-effect evaporator for a 5 ton/h processed tomato juice initially at 5% concentration to 35% tomato paste concentration. The steam economy (SE) was reduced from 3.7 at an interval of 0.4 to study its effect on the outlet tomato paste concentration. Based on some thermodynamic assumptions, the effect of varying some input variables on the output parameters was studied. Other values of SE were later assumed and the process repeated until the desired 35% tomato paste concentration was obtained. The desired concentration was obtained in the third effect when a steam economy of 2.1 was used. With this SE of 2.1, the concentration of tomato paste obtained in first effect is 11%; second effect is 7% while the target concentration of 35% is obtained in the third effect. It was concluded that most of the output parameters, such as tomato paste concentration; water removed; volumetric flow rate; and area decrease with increasing SE; only mass of flow rate increases with increasing SE. Also, the tomato paste concentration increases as the number of effect increases; with a tomato paste concentration of 35% obtained in the third effect. The choice of SE and the number of effects should be properly considered before the design of tomato paste production facility.

Keywords: Triple-effect; evaporator; tomato paste production; MATLAB.

NOMENCLATURES

x_1 : *Inlet composition of tomato juice feed*
x_2 : *Outlet composition of concentrated tomato paste*
SE : *Steam economy*
M_F : *Mass flow rate of tomato juice feed (kg/h)*
T_F : *Temperature of tomato juice feed (K)*
T_S : *Temperature of saturated steam to first effect (K)*

1. INTRODUCTION

Tomato (*Lycopersicum esculentum*) is a seasonal and most widely used agricultural commodity which can be converted to a wide range of products. Grown in many regions of the world [1]; processed tomato products account for 80% of total tomato consumption. United States Department of Agriculture's Economic Research Service (USDA ERS) estimates suggest the largest use of processed tomatoes is for sauces which account for 35%, followed by tomato paste, 18%; canned whole tomato products, 17%; ketchup and juice, each about 15% [2]. Some studies on tomatoes have been carried out by some researchers. Foda and McCollum [3] reported on the viscosity of tomato juice as influenced by its constituents. Luh and Daoud [4] reported on the effect of break temperature and holding time on pectin and pectic enzymes in tomato pulp. Crandall and Nelsoq [5] studied the consistency of tomato juice and puree as affected by preparation and milling. Farrokh and Bor [6] studied the quality factors of tomato pastes made at several break temperatures. The evaluation of the stability of tomato and sunflower oil microconstituents in systems modeling the processing of tomato paste into tomato sauce by [7]; biopreservation of tomato paste and sauce with *Leuconostoc* spp. metabolites by [8] are some recent work.

Industrial processing of tomatoes began in Italy, Portugal, Spain and the USA around 1900; and in terms of global trade in tomato paste, China is now the world's largest exporter. A worldwide tomato processing industry has since evolved with a range of technologies which are able to convert tomatoes into products such as paste, sauces and ketchup. In the industrial market, tomato paste is probably the most important product as it is used globally as an ingredient in preparing meals and food products; valued in household for thickening and adding depth of flavour to sauces and stews and used as basis for a wide range of other products. It is technically classified according to its dry matter content. Single concentrate having 12-14% of dry matter; double concentrate (the most common form of tomato paste) with 28-30% dry matter and triple concentrate with 36-38% dry matter [9]. A good feature of tomato paste is that it transforms a product that is in its ripe form, which has a short shelf-life and extremely hard to transport without damage into a durable long-life form. This feature is a key to the growth of the tomato industry as it allows tomato products be sold over a wide geographical region and outside of the relatively short harvest period.

Tomato concentrate production can be classified as either Hot Break (HB) process or Cold Break

(CB) process. HB process is when the fresh tomato is chopped when heated, at temperatures ranging from 85-95°C, resulting in a more viscous, but less flavoured paste which is usually used for ketchup and different sauces. CB process involves chopping the fresh tomato at lower temperatures, ranging from 65 to 75°C, resulting in a less viscous, but slightly better flavoured paste which is mainly used for triple concentrate paste packed for domestic use. The decision whether the product will be a HB or CB type is chosen well in advance of the processing period, during the cultivation period.

1.1 Review on Tomato Paste Production

Tomato processing facility requires constant supply of tomatoes for the line to operate at maximum capacity, as fresh and ripe tomatoes cannot be kept waiting for processing at temperatures of over 30°C for more than 24-48 h (this will cause an inferior finished product quality). Also, every time the tomato processing line is shut down, all the machinery must be cleaned, with the subsequent loss of several working hours, wastage of both large amount of water and product contained in the evaporator. Therefore, fresh tomatoes arriving at the plant are unloaded into a collection channel (also known as flume), which is a stainless steel or cement duct into which a quantity of water 3 to 5 times higher than the amount of unloaded tomato is continuously pumped. Water plays a very important role during the offloading of the tomatoes into the flume. A vast quantity of it is pumped inside the delivery truck so that the tomatoes can be gradually feed into the flume without getting damaged; and during the rinsing of the tomatoes under a clean water spraying system and its conveyance through a roller elevator to a sorting station.

At the sorting station, the green, damaged and substandard tomatoes; any foreign matter and remaining roots, stems and leaves are removed by placing on a reject conveyor. The tomatoes suitable for processing are transported to the chopping station (mostly consisting of a hammer mill) where they are chopped. The tomato pulp (consisting fiber, juice, skin and seeds) is pre-heated to 65-75°C for a CB process. The heated pulp is then conveyed via a special pump to an extraction unit composed of two operating stations: A pulper and a refiner, equipped with sieves having different sized meshes. Two products, the refined juice for concentration and the waste for disposal come out of the extraction unit. The yield from extractor (about 95%) varies according to the variety of tomatoes treated, pulp's temperature (a higher temperature increases juice yield), type of sieve fitted, the rotation speed and shape of the rotor on each operating stations.

The refined juice is collected in a large storage tank which constantly feeds an evaporator. The juice inside the evaporator passes through different effect(s) where its concentration level is gradually increased until the required density is obtained. The paste from the evaporator is fed directly into an aseptic system tank via a pump at high pressure to an aseptic sterilizer-cooler (operating at about 35-38°C) and then to an aseptic filler, where it is filled into pre-sterilized aseptic bags. The packaged concentrate can be kept up to 24 months depending on the ambient conditions.

1.2 Review on the Evaporation System

The evaporator is a unit that partially removes water from liquid feeds by boiling off water vapour thereby concentrating the feed. It is used to pre-concentrate feed and hence reduce its weight and volume. This eventually reduces storage, transport and distribution costs. The rate of evaporation is determined by both the rate of heat transfer into the feed and the rate of mass transfer of vapour from the feed. There could be single-effect evaporator or multiple-effect evaporators. During evaporation, sensible heat is transferred from steam to raise the temperature of the feed to its boiling point; therefore energy is the most important running cost item during the process. There is wastage of energy in a single-effect evaporator as the latent heat of the vapour is not used but discarded. It is mostly used when a cheap supply of steam is available; when throughput is low; when the vapour is contaminated that it cannot be reused or the feed is corrosive that expensive materials of construction must be used. Whereas a multiple-effect evaporator is based on the repeated use of water vapour from one evaporation unit (called effect) to heat the next effect which operates at a lower pressure. The first effect thus acts as a steam generator for the second effect which acts as a condenser to the first and so on. For each kilogram of water evaporated in a multi effect evaporator, the quantity of steam consumed and the quantity of cooling water utilized in the condenser are inversely proportional to the number of effects [10]. Thus, 1 kg of steam can evaporate more water, depending on the number of effects and the operating pressures. The SE in a multiple-effect system is higher than 1, but less than the number of effects. Typical steam economies for industrial evaporators are already reported by [11,12].

2. METHODOLOGY

In order to achieve maximum profitability, manufacturers of tomato paste need processing equipment that is modular in construction and versatile enough to handle a wide range of products. Also, since energy can be saved by reusing vapour formed from one effect to the other, a triple-effect evaporator is considered for this study for a 5000 kg/hr tomato juice initially at a concentration of 5% to a tomato paste of 35% concentration using CB process. Changes to product quality that result from relatively severe heat treatment are minimized by the design and operation of the equipment. For this study, the evaporator therefore works at reduce pressure and temperature (significantly below 100°C). The reduced pressure is obtained by combining condensers with vacuum pumps to the vapour from the evaporator. For this work, mass flow rate of product for each effect and the water removed in each effect were calculated. Mass of steam required to achieve separation was also calculated by assuming SE values. MATLAB was used in analyzing the design and operation of the triple-effect evaporation system by initially testing with a SE of 2.5 (based on previous report by some authors) in order to study its effect on the outlet tomato paste concentration, and then reducing and assuming new values of SE from 3.7 (at an interval of 0.4) each time until desired product concentration is obtained. The area, number of tubes and volumetric flow rate of the pump in each effect was also calculated. The thermodynamic properties of steam are taken from steam tables [13].

2.1 Assumptions

1. The tomato juice/paste in the evaporator is assumed to be completely mixed
2. The tomato juice entering the evaporator and the concentrated tomato paste leaving the evaporator has the same composition
3. The boiling point elevation of tomato juice is relatively small and therefore neglected
4. The specific heat (C_p) of tomatoes juice at 5% concentration is taken as 4.9 kJ/kg K and that of tomato paste at 35% concentration as 3.02 kJ/kg K
5. No heat is lost by radiation or convection

2.2 Mathematical Modeling of the Triple-Effect Evaporator

The known parameters for the process are given in Table 1. The other input variables are listed in Appendix 1.

Table 1. Known parameters for the triple-effect evaporator

SN	Parameter	Value
1	No of effects	3
2	M_F	5000 kg/h
3	T_F	35°C
4	x_1	0.05
5	x_2	0.35
6	T_S	100°C

3. RESULTS AND DISCUSSION

The results obtained for the output parameters for a steam economy of 2.1 are given in Table 2. It can be seen from the table that a target tomato paste concentration of 35% was obtained from the third effect. It is observed that the tomato concentration increases as the number of effect increases. Also the mass flow rate of product; the area; the number of tubes; and the volumetric flow rate of the pump decreases as the number of effect increases.

A plot of tomato concentration against steam economy for the different effects is shown in Fig. 1. It can be seen that the tomato juice concentration increases with decreasing steam economy. The target tomato paste concentration of 35% was obtained in the third effect when the steam economy of 2.1 was used. There is no remarkable change in concentration of tomato juice in first effect with different changes in steam economy. With a steam economy of 2.1, the concentration of tomato paste obtained in first effect is 11%; second effect is 7% while the target concentration of 35% is obtained in the third effect.

Figs. 2 to 5 show the plots of some output parameters against SE for the different effects. The profiles for first effect, second effect and third effect show similar trends as shown in the plots. Most of the output parameters, such as tomato paste concentration; water removed; volumetric flow rate; and area decrease with increasing SE; only mass of flow rate increases with increasing SE as shown in Fig. 3. Close values were noticed at SE of 2.1, 2.5 and 2.9 in second and third effect for the water removed; volumetric flow rate; and area as shown in Figs. 2, 4 and 5.

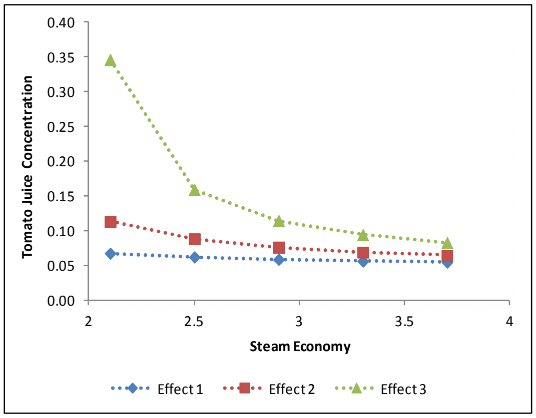

Fig. 1. Tomato juice concentration versus steam economy for the different effects

Fig. 6 shows the plot of concentration against the number of effects for the steam economy of 2.1 which produced the target tomato concentrate. It can be seen that the tomato paste concentration increases as the number of effect increases; with a tomato paste concentration of 35% obtained in the third effect.

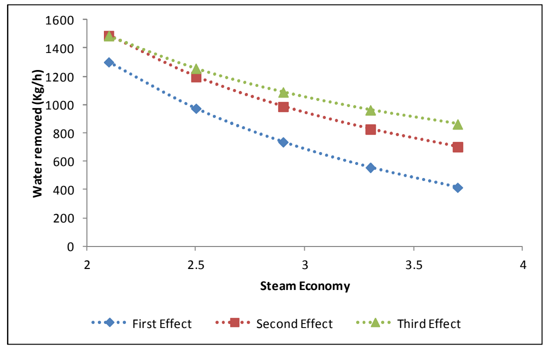

Fig. 2. Water removed versus steam economy for the different effects

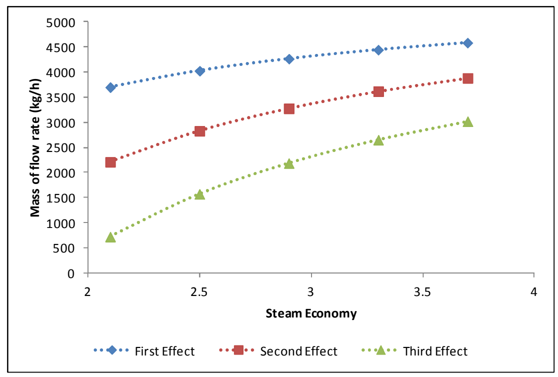

Fig. 3. Mass flow rate versus steam economy for the different effects

Table 2. The results obtained as output parameters for steam economy of 2.1

Output parameters	Value
The reduced tomato juice concentration in first effect	0.07
The reduced tomato juice concentration in second effect	0.11
The tomato paste concentration in third effect	0.35
Mass of flow rate of product obtained from first effect	3,698.46 kg/h
Mass of flow rate of product obtained from second effect	2,210.12 kg/h
Mass of flow rate of tomato paste product obtained from third effect	722.47 kg/h
Water removed in first effect	1,301.54 kg/h
Water removed in second effect	1,488.34 kg/h
Water removed in third effect	1,487.65 kg/h
Area in first effect	367.26
Area in second effect	225.11
Area in third effect	202.15
Number of tubes in first effect	1,060
Number of tubes in second effect	650
Number of tubes in third effect	583
Volumetric flow rate of the pump in first effect	15,571.73 m^3/s
Volumetric flow rate of the pump in second effect	5,852.78 m^3/s
Volumetric flow rate of the pump in third effect	4,722.26 m^3/s

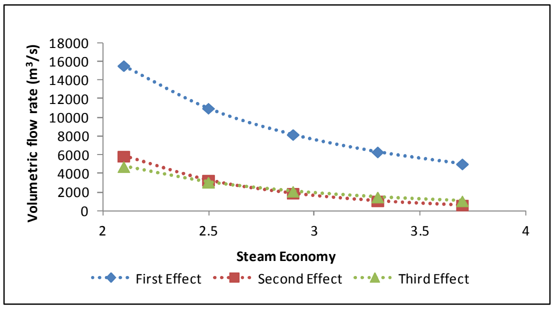

Fig. 4. Volumetric flow rate versus steam economy for the different effects

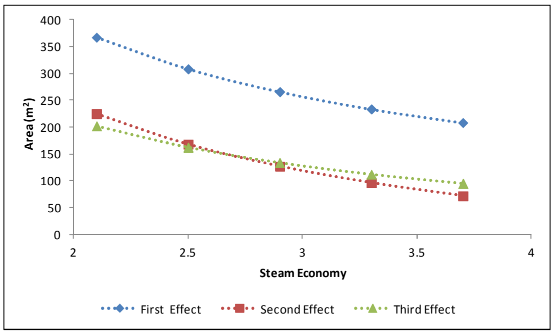

Fig. 5. Area versus steam economy for the different effects

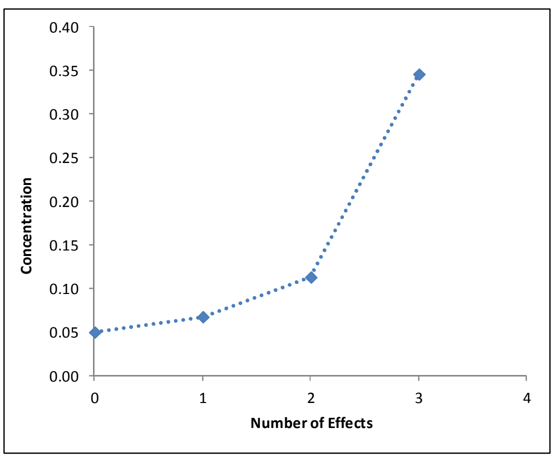

Fig. 6. Concentration versus number of effects for steam economy of 2.1

4. CONCLUSION

The implementation of MATLAB to model a triple-effect evaporator for a 5 ton/h processed tomato juice initially at 5% concentration to 35% tomato paste concentration was adequately studied. Steam economy (SE) was reduced from 3.7 at an interval of 0.4 to check its effect on the concentration of tomato paste obtained. Also, based on some thermodynamic assumptions, the effect of varying some input variables on the output parameters were studied. Other values of SE were later assumed and the process repeated until the desired 35% tomato paste concentration was obtained. The desired tomato paste concentration of 35% was obtained in the third effect when a steam economy of 2.1 was used. With this SE of 2.1, the concentration of tomato paste obtained in first effect is 11%; second effect is 7% while the target concentration of 35% was obtained in the third effect. The choice of SE and the number of effects should be properly considered before the design of tomato paste production facility.

The primary by-product (pomace) from tomato paste production is a mixture of peels, seeds and pulp. This can be produced in quantities as much as 5-10% of the weight of tomatoes taken in for processing [14]. It has high moisture content (around 75%) and difficult to transport as it spoils quickly [15]. Researchers have suggested uses as biolacquer for the protection of metal food packaging in order to increase their economic and commercial competitiveness, by improving the quality of the metal cans [16]. It also serves as a potential ingredient in functional foods [17]. Other waste produced is the considerable quantities of waste water.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX 1

Input Variables

Please enter the value of Inlet composition of tomato juice feed, x_1:0.05
Please enter the value of Outlet composition of concentrated tomato paste, x_2:0.35
Please enter the value of steam economy:2.1
Please enter the value of latent heat of vapour in first effect:2283.0
Please enter the value of latent heat of vapour in second effect:2309.0
Please enter the value of latent heat of vapour in third effect:2346.60
Please enter the value of mass flow rate of tomato juice feed:5000
Please enter the specific heat of tomato juice feed:4.9
Please enter the temperature of tomato juice feed:35
Please enter the latent heat of steam to first effect:2257
Please enter the specific heat of condensate in first effect:4.216
Please enter the specific heat of condensate in second effect:4.205
Please enter the specific heat of condensate in third effect:4.196
Please enter the temperature of saturated steam to first effect:100
Please enter the temperature at which evaporation takes place in second effect:90
Please enter the temperature at which evaporation takes place in third effect:80
Please enter the specific heat of product in first effect:4.9
Please enter the specific heat of product in second effect:3.96
Please enter the specific heat of product in third effect:3.02
Please enter the temperature of product coming out from first effect:91
Please enter the product temperature coming out from second effect:79
Please enter the product temperature coming out from third effect:63
Please enter the difference between steam inlet temperature and product outlet temperature in first effect:9
Please enter the difference between steam inlet temperature and product outlet temperature in second effect:11
Please enter the difference between steam inlet temperature and product outlet temperature in third effect:17
Please enter the diameter of tube:27.58
Please enter the length of tube:4
Please enter the overall heat transfer coefficient in first effect:1400
Please enter the overall heat transfer coefficient in second effect:1200
Please enter the overall heat transfer coefficient in third effect:1000
Please enter the velocity of flow:0.04

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