Preliminary study on the utilization of geothermal energy for drying of agricultural product

Andri Cahyo Kumoro[1)] and Dedy Kristanto[2)]
[1)] Department of Chemical Engineering, Faculty of Engineering,
Diponegoro University, Semarang, Indonesia.
[2)] Department of Petroleum Engineering, Faculty of Mineral Technology,
Universitas Pembangunan Nasional "Veteran" Yogyakarta, Indonesia.
E-mail: baguscahyo@yahoo.com, dedykris@yahoo.com

Abstract

Indonesia is highly rich in natural resources. Volcanoes are spread over the Sumatra, Java, Bali and Nusa Tenggara islands in connection with a Mediterranean circumferential. The rest are volcanoes in Sulawesi, the Maluku archipelago and Northern Papua in connection with a Pacific circumferential. Volcanic activities create a potential source of geothermal energy. One of the famous geothermal energy centres in Indonesia is the Dieng plateau. It is also well known for tobacco and mushroom plantations. However, due to the heavy rainfall and drying problems the quality of the tobacco produced here is somehow still below the international standard. Therefore, a research into the utilization of geothermal energy for tobacco drying becomes very important. The research into the drying of tobacco leaves was conducted using an indirect heating system. The heat source for the dryer was geothermal steam. A certain amount of sliced tobacco leaves was placed into a tray dryer. Then the steam was kept flowing at a selected velocity. The moisture loss of the tobacco leaves was indicated by direct balancing of the sample and was then recorded at five-minute intervals. The experiment was stopped after one hour since the steam started to leak into the system. Using the moisture loss and time data, a drying rate curve was obtained. The effects of the steam flow rates and the sliced tobacco leaves layer thickness on the drying performance were investigated in this research. Experimental works showed that the increase of steam flow rate can enhance the drying performance, while increasing the layer thickness reduced the drying performance. However the high sulphur content in the steam caused rusting of the tray material and an unpleasant odour was produced.

Keywords: *geothermal energy, drying, tobacco, sulphur.*

1 Introduction

Indonesia is very rich in volcanoes, which are spread out over the Sumatra, Jawa, Bali and the Nusa Tenggara islands in connection with Mediterranean circumferential and Sulawesi, Maluku archipelago and Northern Papua in the connection with Pacific circumferential. The volcanic activities create a potential source of geothermal energy. Data collected by Pertamina (Indonesian State owned Oil and Gas Company) in 1998 indicated that the geothermal energy potential of the Indonesian resources was about 20.000 MW spread out over almost all its territory (Devisi Panas Bumi, Pertamina, Juni 1999). Twelve geothermal energy fields were explored upto the year 1998, four fields were commercialized by Pertamina, while the rest were exploited in joint venture between Pertamina and other private companies. The total production was 2,690,997,219 KWh. One of the famous geothermal energy areas in Indonesia is the Dieng plateau. Dieng has 27 geothermal fields and 12 wells, which have the potential of producing electrical power of more than 1,400 MW (Devisi Panas Bumi, Pertamina, June 1999).

The Dieng plateau is also well known for tobacco and mushroom growing. When the tobacco leaves have reached the desired yellow colour and are thoroughly wilted, the leaves must be dried. However, due to the heavy rainfall and drying problems the quality of the tobacco produced in Indonesia is still below international standard. Therefore, a research into the utilization of geothermal energy for tobacco drying is very important.

2 Review of drying technology

Drying is very important to the conservation of agro–products in the food industry. For tobacco drying is critical because tobacco is sensitive to temperature changes. Impatience to capture a good colour often results in a tendency to increase the temperature too rapidly, and thereby cause a browning or barn scald. On the other hand if the temperature is increased too slowly, sponging may occur. Thus close control of airflow and temperature is mandatory during leaf drying to prevent undesirable colour in the cured leaf. To prevent sponging, the leaf needs to be dried as rapidly as possible, but at a rate so high as to cause scalding. For tobacco leaves (which are hygroscopic), the moisture held within them is usually bound moisture, such as moisture trapped in closed capillaries, the water component of juices or water held by surface forces, as well as unbound water held within the material by the surface tension of the water itself (Howe, 1980). There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period.

2.1 Constant drying rate period

During the constant drying period, drying takes place from the saturated surface of the material by diffusion of the water vapour through a stationary air film into the air stream and is simply the evaporation of moisture from the free water surface. The rate of moisture removal during this period is mainly dependent on the surrounding conditions and only slightly affected by the nature of the materials. The end of the constant drying rate period is marked by a decrease in the rate of moisture migration from within the material below that which is sufficient to replenish the moisture being evaporated from the surface. At this stage, which defines the critical moisture content, the ambient conditions cease to play much role in the rate of drying.

Ambient factors, namely the vapour pressure difference between the drying air and the wet surface, the surface area of the product exposed to the drying air, the mass transfer coefficient and the drying air velocity, are related to the drying rate according to the following formula (Hall, 1980):

$$\frac{dW}{dt} = \frac{K_m A_s}{R_o T}\left(P_v - P_{va}\right) = K_f A_s \frac{\left(T_a - T_s\right)}{\lambda_{vap}} \tag{1}$$

where the thermal conductance of the air film, K_f and mass transfer coefficient, K_m are a function of the air velocity. W is the mass of moisture (kg) transferred into drying medium. While, $\left(P_v - P_{va}\right)$is the vapour pressure difference between air at the condition studied and at its respective saturated condition (atm) T, *whereas* T_a and T_s are the equilibrium temperature of drying medium (air) and the drying material (solid) at the operating condition studied, temperature of drying medium (air) and temperature of the solid surface at the condition studied respectively (°K). λ_{vap} is heat of vaporisation of the moisture, (kkal/kg moisture). R_o and A_s are the ideal gas constant (kkal atm/mol °K) and effective surface area (m). The above equation also suggests that the rate of drying is independent of the geometrical shape of the surface of the material.

2.2 Falling drying rate period

In the falling drying rate period the material surface is no longer capable of supplying sufficient moisture to saturate the air in contact with it (Hall, 1980). This drying rate regime is dependent essentially on the rate of diffusion of moisture from within the material to the surface and also on moisture removal from the surface. It is subdivided usually into two stages, namely the first falling drying rate period which involves the unsaturated surface drying and the second falling drying rate period where the rate of moisture diffusion to the surface is slow and is the determining factor (Hall, 1980).

2.3 Drying time

The time of drying is the summation of the time needed in the constant drying rate period (t_{cr}) and falling rate period (t_{fr}). This may be represented by the equation:

Constant rate period,

$$t_{cr} = \frac{(M_{db\,o} - M_{dbc})}{R_{cr}} \tag{2}$$

or $M_{db} = M_{dbo} - R_{cr}t; M_{db} \geq M_{dbc}; t \leq tc$, where R_{cr} is the constant drying rate, (kg water/kg dry solid/s). $M_{dbo,}$ M_{db} and M_{dbc} are the initial moisture content, moisture content at corresponding time and critical moisture of the material in dry basis (kg water/kg dry solid), respectively.

$$M_{db} = \frac{W_o - W_d}{W_d} \tag{3}$$

where W_o is initial weight of the drying material, while W_d is the weight of dry material.

Falling rate period,

$$t_{fr} = \frac{\left(M_{dbc} - M_{dbeq}\right)}{R_{fr}} \ln\left[\frac{\left(M_{dbc} - M_{dbeq}\right)}{M_{db} - M_{dbeq}}\right] \tag{4}$$

where R_{fr} is the falling drying rate, (kg water/kg dry solid/s), M_{dbeq} is the moisture content of the material at equilibrium with the moisture content of the drying air used in the experiment, (kg water/kg dry solid). Therefore, it is obtained that $t = t_{cr} + t_{fr}$

3 Methodology

3.1 Material

The sliced tobacco leaves were used here as the material to be dried. The initial moisture content of the tobacco leaves was a 75% wet basis, but the equilibrium moisture content of the tobacco leaves was close to zero. The steam used here was saturated geothermal steam generated in a geothermal steam generator system at a pressure of 1 atmosphere.

3.2 Experimental apparatus

A cabinet-type dryer similar to the tobacco-barn dryer was chosen for the farmer option. The size of the dryer was designed to be 1.2 m x 1.2 m x 2.4 m with the front-loading of 10 rectangular trays. Each tray can handle up to approximately 10 kg of product. The housing of the dryer was made of concrete block with corrugated galvanized iron sheet roofing. The heat from the steam generated by geothermal energy was supplied to the dryer by a multitubes located at the bottom of the dryer. The steam from the steam generator flew through the multitube bundle, which was 0.15 m in diameter and 8 m in length. There were three openings at the bottom of the dryer to provide the ventilation for the dryer. To increase the rate of ventilation by natural draft, a rectangular chimney made of galvanized iron sheet was installed at the top of the dryer. Figure 1 illustrates the tray dryer used for tobacco leaves drying.

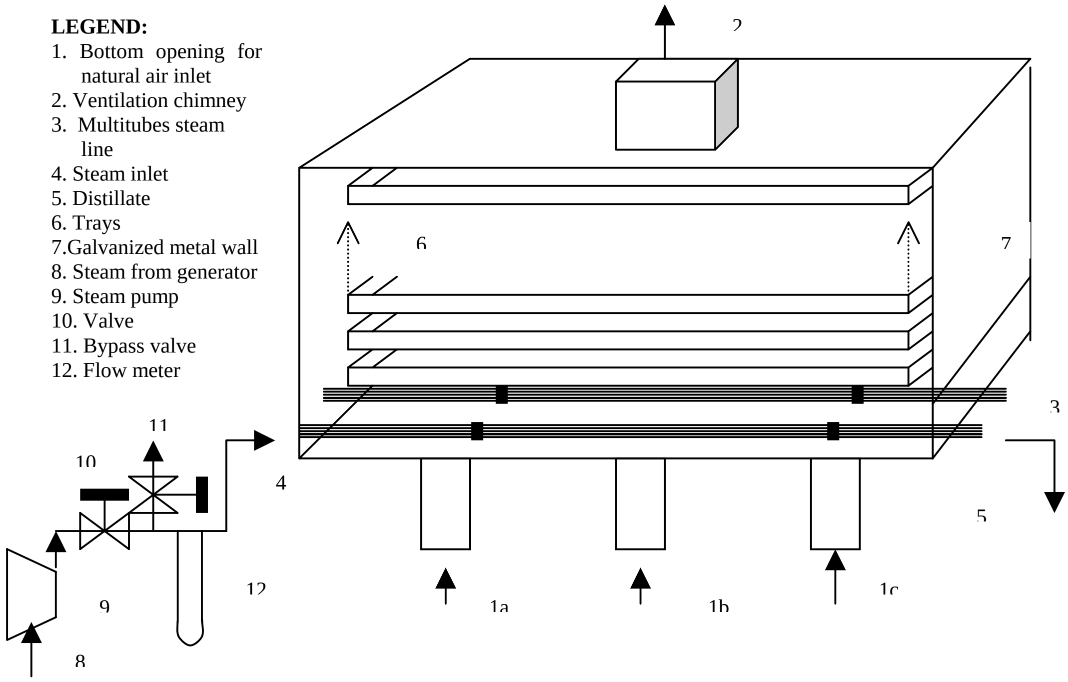

Figure 1: Experimental rig used for drying of tobacco leaves.

3.3 Experimental procedure

A pre-determined quantity of sliced tobacco leaves was placed into a tray dryer. Then the steam was admitted at a selected velocity. The moisture loss of the tobacco leaves was indicated by direct balancing of the sample and was then recorded at five-minute intervals. The experiment was stopped after two hours since the steam started to leak into the system. The drying rate curve was obtained using the moisture loss and time data from the test. The effects of steam flow rates and the layer thickness of the sliced tobacco leaves on the drying performance were investigated in this research.

4 Results and discussion

4.1 Effect of the steam velocity to the tobacco leaves drying rate

Increasing the flow rate of the heating medium (Chandran, et al., 1990; Thomas and Varma, 1992; and Chen, et al., 2001) significantly increases the drying rate in the constant rate periodby. This is due to decrease in gas film resistance surrounding the particle. However, this effect will be significant when the external diffusion controls the rate of drying.

The influence of steam flow rate on the falling rate period is small, however, since the gas film resistance plays a minor role (Kannan, et al., 1995). The steam velocity in this experiment plays a role in supplying the heat. Figure 2 shows the drying process conducted for a 9 cm thickness of the tobacco layer. It is clear that the higher steam velocity gave the higher drying rate. This phenomenon is indicated by the time needed to achieve the desired value of final moisture content being shorter for higher steam velocity, and vice versa. When the steam velocity is high, the flow pattern inside the tube tends to follow the plug flow pattern. The high turbulence of the steam flow increases both the contact between the steam and the tubes wall and the convective heat transfer from the condensed steam to the tube surface (Kern, 1950; Perry and Chilton, 1973). Finally, the conductive heat transfer from the tube surface to the tobacco leaves layer is also increased. Then the drying rate of the tobacco leaves is higher because there is more heat available in the drying system. It is also reasonable, that the increase during falling rate period is due to the tobacco leaves attaining a higher temperature, which increases intraparticle moisture diffusion to the surface. An unpleasant odour was produced, however, when high velocity steam was admitted into the system. This is because the high sulphur content of the steam causes rusting of the tubes and trays.

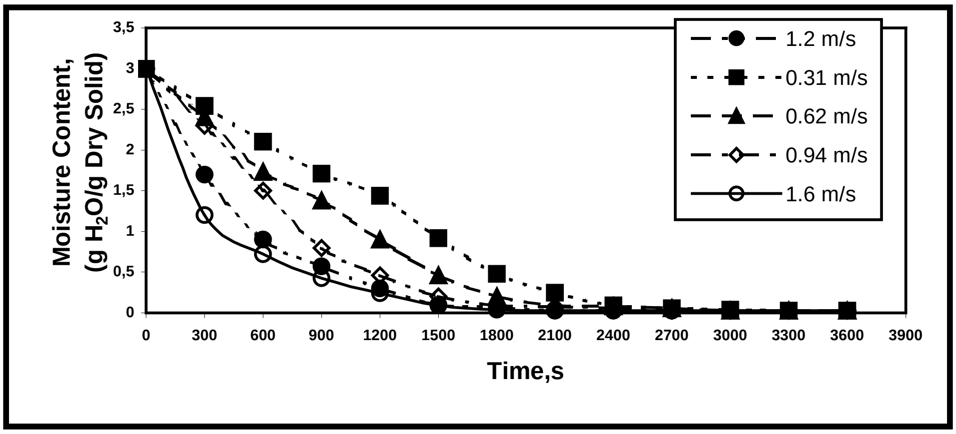

Figure 2: Effect of the steam velocity on drying rate of tobacco leaves.

4.2 Effect of layer thickness on the drying rate of tobacco leaves

Figure 3 shows the effect of layer thickness of the tobacco leaves on the drying rates at a steam velocity of 0.62 m/s. The layer thickness of the sliced tobacco leaves influences the efficiency of the heat transfer from the tubes surface to the layer of sliced tobacco leaves.

Since the conductivity of the sliced leaves is very low, the conductive heat transfer in the layer is very slow. Therefore, increasing the layer thickness lowers the drying rate. Once the layer thickness exceeds 12 cm, no significant change in drying rate is observed.

This result agrees well with the theory proposed by Temple (2000) that the air inside the lower part of the tray dryer is exhausted at saturation. For the thick layers, there is thus no saturation at all after a few seconds; partially dried material in the upper layer will be in contact with the saturated air moving up from the lower layer. This partially dried material will be re-wetted and the air moving away from saturation. If the air is not at saturation, then the equilibrium relative humidity of the material will limit the degree of saturation of the exhaust air.

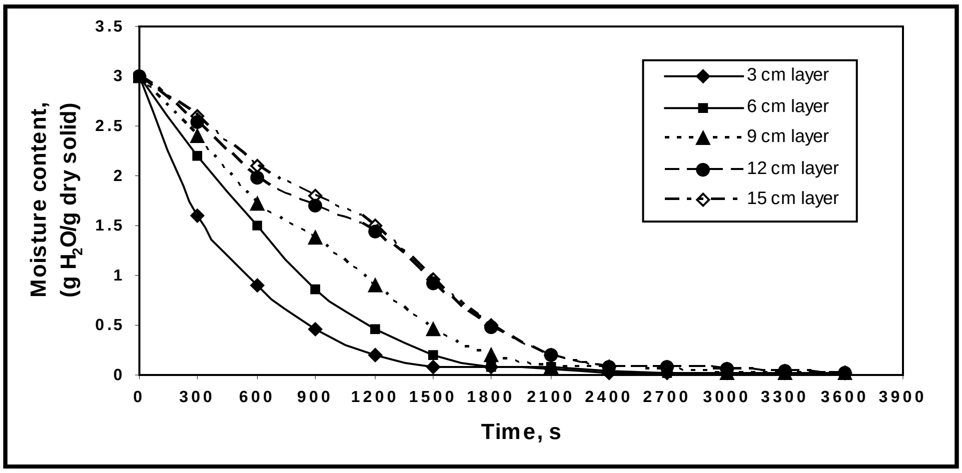

Figure 3: Effect of layer thickness on the drying rate of tobacco leaves.

5 Conclusions

From the experimental results and theoretical analysis, it can be concluded that increasing steam velocity may enhance the drying performance, while increasing the layer thickness reduces drying performance. It was moreover observed that the high sulphur content in the steam caused rusting of the tray material and produced unpleasant odour.

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Removal of boron from Kizildere-Denizli geothermal brines using ion-exchange method

Mebrure Badruk
MTA Aegean Region Management, Izmir, Turkey,
E-mail: mbadruk@hotmail.com
Nalan Kabay
Ege University Chemical Engineering, Izmir, Turkey

Abstract

The first geothermal power plant of 20 MW in Turkey was installed in Denizli-Kizildere geothermal field located in the Western Anatolia. The water disposed of from the power plant is about 800-1000 tons/h, and its boron content of approximately 30 mg/dm^3 is on the high side to use for irrigation in agricultural areas. It is particularly detrimental to citrus fruits. In order to be able to utilize this brine wastewater for irrigation, the maximum content of boron need to be reduced to less than 1 mg/dm^3. This paper describes research work, investigates optimum conditions for utilizing ion-exchange methods to remove boron from Denizli-Kizildere Geothermal wastewater.

Keywords: *boron removal, ion exchange, geothermal brine, boron*

1 General information

1.1 Introduction

Borates are defined as salts or esters of boric acid, a compound containing the radical B_2O_3 (Bates, 1987). Boron is found in the earth's crust at an average concentration of about 10 ppm (Smith, 1958). Boron is not found free in nature but is always bound to oxygen (Baudis and Fichte). Boric acid borate buffer mixtures serve as pH standard and occur in natural aqueous systems. From the results it is clear that, in addition to the mononuclear boric acid and orthoboric ion to be trigonal ($B(OH)^3$) and ($B(OH)^{-4}$) species, a number of polyborate ions are also formed (Mesmer et al., 1972).

$$B(OH)^3 + H_2O \rightarrow B(OH)^{-4} + H^{+1} \text{(Xiao et al., 1991)} \quad (1)$$

The occurrence of boron varies depending on the pH of the water. In acidic waters (pH<6) orthoboric acid is dominant. Tetra-pentha-hexa and other polyborates are common in neutral and alkaline natural waters. Dissolution of alkaline metallic borates in aqueous media is faster than the others and dissolution rate of borates in general increases with increasing temperature. Therefore in hydrothermal media boron migrates quickly. Boric acid dissolves faster in hot waters than cold waters. There are two kinds of boron species, $B(OH)^3$ and $B(OH)^{-4}$, in a diluted aqueous solution. The predominant boron species (above 90%) in the brine (pH 7.7) is neutral $B(OH)_3$ according to above equation. Therefore, the following surface chelation mechanism is suggested in literature (Ooi et al., 1996) on boron adsorption

$$X\text{-}OH + B(OH)^3 \rightarrow X\text{-}O\text{-} B(OH)^2 + H_2O \quad (2)$$

1.2 Toxicology of boron

Boron is needed in relatively small amounts, however and it becomes toxic, if present in amounts appreciably greater than needed. For some crops 1 to 2 mg/l may be toxic, if 0.2 mg/l boron in water is essential (Ayers, 1994). Experimental laboratory data indicate that this compound is only slightly toxic for animals and humans.

1.3 Ion exchange resins

Ion exchange process is becoming more extensively used in water and wastewater treatment (Dorfner, 1991). Ion exchange resins are polymers carrying fixed functional groups. Functional groups are charged acidic or basic or chelating group attaching to the polymer matrix. The charge of the group is normally compensated by an exchangeable ion. All cyclic ion exchange process includes sorption, elution and regeneration stages. Elution and regeneration can be integrated in one step. Washing steps (if needed) can be incomplete (Zagarodni, 1997).

2 Experiments

2.1 Materials

The characteristics of the Kizildere geothermal brine are summarized in Table 1. All resins were dried at 40°C under vacuum prior to their use. Boric acid solutions were prepared from an analytical grade H_3BO_3 and deionized water obtained from a water purification system. All other materials were reagent grade and used as received.

Table 1: The properties of Kizildere geothermal brine.

pH	: 9.30	Total hardness (AS°)	: 0.06
Specific Conductivity (μmho/cm)	: 4120	Temporary Hardness(AS°)	: 0.06
Evaporation Residual (180°C)(mg/dm^3)	: 4108	Permanent Hardness (AS°)	: 0
K^+ (mg/dm^3)	: 145	HCO_3^- (mg/ dm^3)	: 1037
Na^+ (mg/dm^3)	: 1300	CO_3^{2-} (mg/ dm^3)	: 780
NH_4^+ (mg/ dm^3)	: 3.5	SO_4^{2-} (mg/ dm^3)	: 695
Ca^{2+}(mg/ dm^3)	: 0.39	Cl^- (mg/ dm^3)	: 134
Mg^{2+} (mg/ dm^3)	: 0.08	I^- (mg/ dm^3)	: 4.6
Fe (total) (mg/ dm^3)	: <0.05	I^- (mg/ dm^3)	: 4.6
As (total)(mg/ dm^3)	: 0.58	F^- (mg/ dm^3)	: 15
B(total)(mg/ dm^3)	: 30.2	NO_2^- (mg/ dm^3)	: < 0.01
Li^+ (mg/ dm^3)	: 4.8	NO_3^- (mg/ dm^3)	: < 1
Al^{3+}(mg/ dm^3)	: 0.71	PO_4^{3-} (mg/ dm^3)	: < 0.1
SiO_2 (mg/ dm^3)	: 415	Br^- (mg/ dm^3)	: 0.53

2.2 Batch sorption

In the experiment 0.25 g of different resins was contacted with 50 cm^3 of 0.01 M H_3BO_3 solution and Kizildere geothermal brine (pH 9) for 48 h at 30°C with continuous shaking. The supernatant (2 cm^3) was taken and analyzed spectrophotometrically using a Carmen method.

2.2.1 Effect of Ca(II) and Na(I) ions on boron sorption

The effect of Na(I) and Ca(II) ions on sorption behaviour of boron has been studied using 0.00125 M $CaCl_2$, 0.0025 M $CaCl_2$, 0.00375 M $CaCl_2$, 0.0075 M $CaCl_2$, 0.5 M $CaCl_2$, 1 M $CaCl_2$, 0.5 M NaCl, 1 M NaCl and 2 M NaCl. For this 0.25 g Diaion CRB 02 Glucamine resin (1-0.250 mm) was contacted with 50 cm^3 of 0.01 M H_3BO_3 solution containing Ca(II) and Na(I) ions at various concentrations. The sorption experiments were performed at 30°C with a continuous shaking for 48 h.

2.3 Column sorption

The chelating resin Diaion CRB 02 was used in column sorption of boron. The columns employed were made of glass of internal diameter ~0.7 cm. Each column was packed with 3.0 cm^3 wet-settled volume of resin. The solution of 0.01 M H_3BO_3 solution and Kizildere geothermal brine was delivered as downflow to the column using a peristaltic pump (Atto SJ-1211 H Model) capable of delivering various flow rates of SV (space velocity: bed volume/h). The breakthrough curves were obtained by analysis of successive 6 cm^3 fractions of the effluent. The fractions were collected using a fraction collector (Advantec SF 2120 Model). The column elution profiles were obtained by the column elution of the resin loaded with boron ions using 1 M HCl for 0.01 M H_3BO_3 solution and 0.25 M H_2SO_4 for Kizildere geothermal brine at SV $5h^{-1}$, collecting 3 cm^3 fractions of effluent.

3 Results and discussion

3.1 Batchwise extraction of boron by different resins

For comparison, various chelating ion exchange resins have been used for batch sorption of boron. The results are presented in Table 2. As shown in Table 2, among the resins tested, Diaion CRB 02, RGB gave the most promising results for boron removal from H_3BO_3 solution and Kizildere geothermal brine. The resins Diaion CRB 02 gave the largest removal (49% for 0.01 M H_3BO_3 and 98% for Kizildere geothermal brine) for boron in the geothermal brine.

3.1.1 Effect of Ca(II) and Na(I) ions on boron sorption

Kizildere geothermal brine contains other ionic impurities such as Na, Ca, Si, K. The effect of Ca(II) and Na(I) ions on sorption of boron was studied using the resins Diaion CRB 02. The results are summarized in Table 3.

3.2 Columnar sorption of boron from 0.01 M H_3BO_3 solution

3.2.1 Effect of SV

Columnar sorption of boron from 0.01 M H_3BO_3 solution was studied at SV 5,10,15 h^{-1} using Diaion CRB 02 (Figure 1). The loaded columns with boron were eluted with 1 M HCl at SV 5 h^{-1} (Figure 2).

Columnar sorption of boron from Kizildere geothermal brine was studied at SV 15 and 25 h^{-1} using Diaion CRB 02 (Figure 3). Breakthrough capacity increased some extent with a decrease in SV. The loaded columns with boron were eluted with 0.25 M H_2SO_4 at SV $5h^{-1}$ (Figure 4).

Table 2: Boron removal by various ion exchange resins from 0.01 M H_3BO_3 solution and Kizildere geothermal brine by various resins.

RESIN	Removal of Boron			
	(%)$^{1)}$	mgB/g-resin$^{1)}$	(%)$^{2)}$	mgB/g-resin$^{2)}$
Diaion CRB 02	49.3	9.68	98.1	6.69
RGB	42.3	8.42	71.6	4.88
Purolite S 108	28.4	5.58	93.6	6.38
Diaion C 200	6.2	1.22	4.2	0.29
Purolite S 940 (0.5-0.355	5.5	1.08	5.5	0.38
Dowex 50W	4.9	0.96	0.0	0.0
Purolite A 103	4.9	0.96	17.3	1.18
RSPO	4.0	0.78	0.0	0.0
Purolite C 106	3.9	0.76	0.0	0.0
Purolite A 500	3.6	0.71	2.2	0.15
Purolite CT 175(0.6-	2.7	0.52	3.9	0.27
Purolite C 150(0.6-0.355	2.3	0.45	3.1	0.21
Diphonix(100-200 mesh)	1.9	0.37	6.6	0.45

$^{1)}$: For 0.01 M H_3BO_3, $^{2)}$: For Kizildere geothermal brine; Sorption : 0.25 g resin, 50 cm^3 solution, 30°C, 48 h

Table 3: Effect of Ca(II) and Na(I) ions boron sorption by Diaion CRB 02(1-0.25 mm).

Solution	Removal (%)	mgB/g-R$^{1)}$
0.00125 M $CaCl_2$ in 0.01 M H_3BO_3	40.9	7.74
0.0025 M $CaCl_2$ in 0.01 M H_3BO_3	43.1	7.95
0.00375 M $CaCl_2$ in 0.01 M H_3BO_3	42.1	8.54
0.0075 M $CaCl_2$ in 0.01 M H_3BO_3	46.9	8.59
0.5 M $CaCl_2$ in 0.01 M H_3BO_3	42.6	8.22
1 M $CaCl_2$ in 0.01 M H_3BO_3	42.6	8.20
0.5 M NaCl in 0.01 M H_3BO_3	42.4	7.67
1 M NaCl in 0.01 M H_3BO_3	41.2	7.39
2 M NaCl in 0.01 M H_3BO_3	42.5	8.09

R$^{1)}$: Resin, Sorption: 0.25 g resin, 50 cm^3 0.01 M H_3BO_3, 30°,48 h

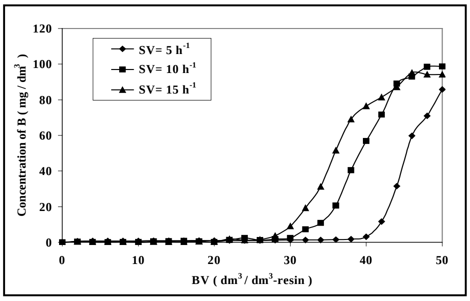


Figure 1: Effect of SV on breakthrough volume of Diaion CRB 02.

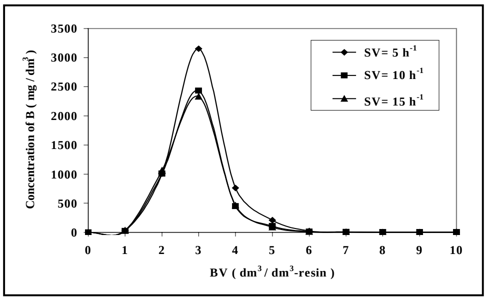
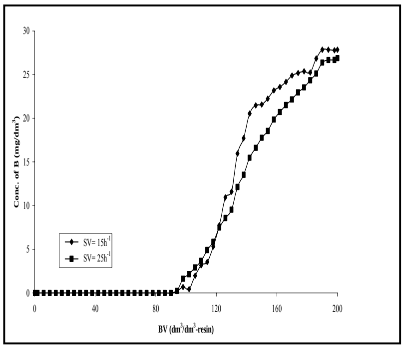


Figure 2: Elution profiles.



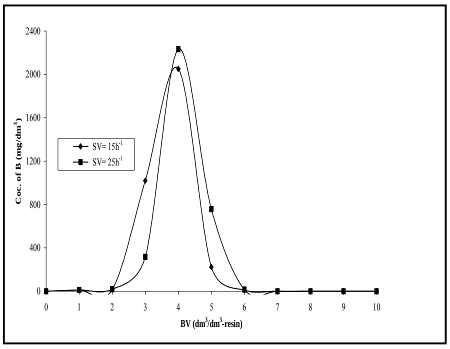
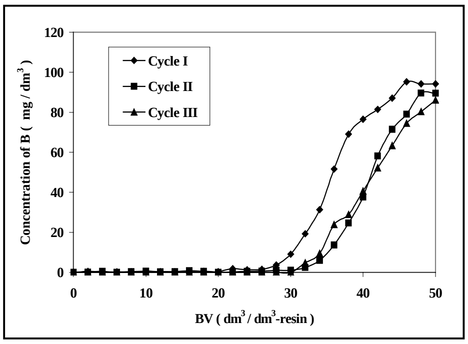


Figure 3: Effect of SV on column sorption of boron from Kizildere geothermal brine.

Figure 4: Elution curves of boron.

3.2.2 Recycle use of diaion CRB 02

Diaion CRB 02 was used to study the recycle use of resin for boron removal from 0.01 M H_3BO_3 solution (Figures 5 and 6). During the third cycle, the breakthrough point remained almost at the same position.



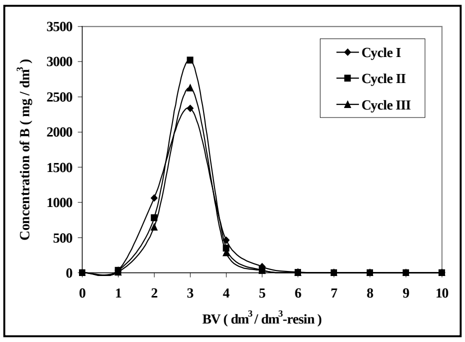
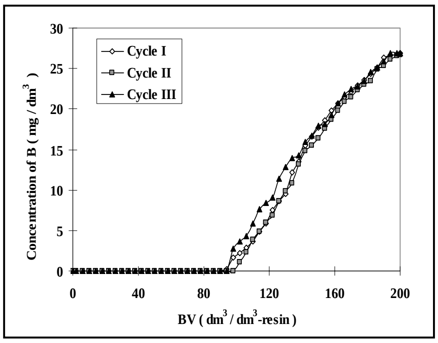


Figure 5: Recycle use of Diaion CRB 02 for boron removal.

Figure 6: Elution profiles.

Diaion CRB 02 was used to study recycle use of resin for boron removal from Kizildere geothermal brine at SV 25 h^{-1} (Figures 7 and 8).



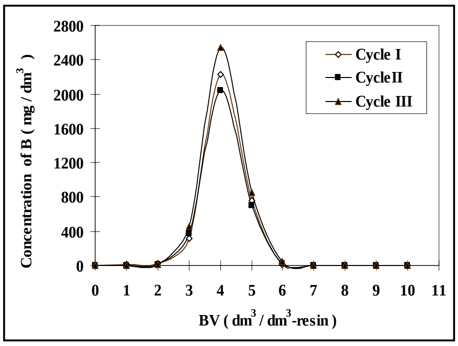


Figure 7: Recycle use of Diaion CRB 02 for boron removal from Kizildere brine.

Figure 8: Elution profiles of boron.

4 Conclusions and recommendations

The geothermal brine from the Kizildere geothermal area contains approximately 30 mgB/dm^3. In order to be able to utilize this brine for irrigation, the maximum content of boron needs to be reduced to below 1 mg/dm^3. N-Glucamine type resin Diaion CRB 02 was found to be the most promising as a sorbent for boron removal from Kizildere geothermal brine.

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Geothermal heating of greenhouses and aquaculture facilties

Tonya L. Boyd and John W. Lund
Geo-Heat Center, Oregon Institute of Technology
Klamath Falls, OR 97601
E-mail: boydt@oit.edu and lundj@oit.edu

Abstract

There are at least 37 greenhouse and 58 aquaculture sites using geothermal energy in the United States. The installed capacity is 119 and 140 MWt respectively. The annual energy use is 1,132 and 3,000 TJ (315 and 833 GWh/yr) respectively. Aquaculture has the largest use of geothermal energy in the U.S. at 35%, and greenhouses amounts to slightly over 13% of the total energy use, if geothermal heat pumps are not considered. These industries have grown 60 and 120% in energy use in the past five years, which amounts to 10 and 17% annual compounded growth. The Geo-Heat Center in Klamath Falls has a technical assistance program to provide advice and preliminary engineering and economic analysis of projects for potential greenhouse and aquaculture developers. The Office of Geothermal and Wind Technologies, U.S. Department of Energy, funds the program.

Keywords: *Aquaculture, catfish, flowers, greenhouses, hydroponics, prawns, roses, Tilapia, vegetables.*

1 Introduction

1.1 Greenhouses

A number of commercial crops can be raised in greenhouses, making geothermal resources in cold climates particularly attractive, where growth can be optimized in a controlled environment. These include vegetables, flowers (potted and cut), houseplants, and tree seedlings. As an example, the optimum growth temperature of cucumbers, tomatoes, and lettuce is shown in Figure 1 (Barbier and Fanelli, 1977). Cucumbers grow best in the temperature range 25 to 30°C, tomatoes near 20°C, and lettuce at 15°C and below. The growing time for cucumbers is usually 90 to 100 days; while the growing cycle for tomatoes is longer, in the range 9 to 12 months. The use of geothermal energy for heating can reduce operating cost (which can amount to as much as 35 percent of the product cost) and allows operation in colder climates where commercial greenhouses using fossil fuels or electricity would not normally be economical. In addition, greenhouses are suited to large quantities of relatively low-grade heat (40 to 50°C and above). Furthermore, better humidity control can be derived to prevent condensation and problems with diseases such as mildew and gray mold (Botrytis) (Schmitt, 1981).

Greenhouses are one of the largest low-enthalpy energy consumers in agriculture (Popovski, 1998). Some of the advantages of using geothermal energy are:

- Good correlation between the sites of greenhouse production area and low-enthalpy geothermal resources,
- Low-enthalpy geothermal resources are common in many countries and area of the United States,
- Geothermal energy requires relatively simple heating installations, but advanced

computerized installations can later be added for total conditioning of the inside climate in the greenhouse,

- The economic competitiveness of geothermal energy for greenhouse heating, especially in colder climates,
- Strategic importance of energy sources that are locally available for food production, and
- Using a geothermal resource in combination with an existing fossil fuel system for peak heating (Rafferty, 1997).

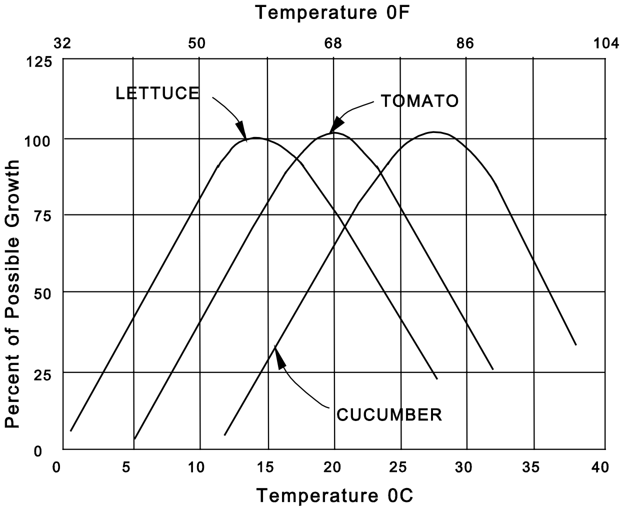

Figure 1: Optimum temperature for growing selected agricultural products.

The use of low-temperature geothermal resources for space heating is fairly simple, often using standard, “off-the-shelf” equipment. If the geothermal fluid is corrosive or causes scaling, a plate heat exchanger can isolate the fluid from the greenhouse heating equipment. Most standard greenhouse heating systems are consisting of: unit heaters with and without a plastic distribution tube, finned pipes, bare tubes, fan coil units, or a combination of these, are adaptable to geothermal. Fossil fuel peaking can be incorporated with the geothermal heat (Rafferty, 1997).

Greenhouses heated geothermally have been in place since the late 1970s in the United States, and today there are approximately 40 applications in 10 western states covering about 44 ha. There are also many installations in about 20 countries, with Hungary, China and Tunisia being the world leaders (Popovski, 1998). These geothermally heated installations cover almost 1,000 ha. These installations are estimated to require between 13 and 27 TJ/yr/ha for heating with about 20 TJ/yr/ha being the average worldwide (Lund and Freeston, 2001).

The heating system design for greenhouses must consider losses from (1) transmission loss through the walls and roof, and (2) infiltration and ventilation losses due to the heating of cold outside air. The design procedure, including heat loss calculations and selection of the heating equipment, is beyond the scope of this paper, but can be found in Rafferty and Boyd (1997) or Rafferty (1998a).

1.2 Aquaculture

Aquaculture involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates. The main species reared in this way are carp, catfish, bass, Tilapia, frogs, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, alligators, mussels and abalone.

It has been demonstrated that more fish can be produced in a shorter period of time if geothermal energy is used for aquaculture pond and raceway heating rather than water dependent upon the sun for its heat. When the water temperature falls below the optimal values, the fish lose their ability to feed because their basic body metabolism is affected (Johnson, 1981). A good supply of geothermal water, but virtue of its constant temperature, can therefore "outperform" even a naturally mild climate.

Optimum temperature is generally more important for aquatic species than land animals, which suggests that the potential of geothermal energy in aquaculture may be greater than in animal husbandry, such as pig and chicken rearing (Barbier and Fanelli, 1977). Figure 2 shows the growth trends for a few land and aquatic species (Beall and Sammels, 1991). Land animals grow best in a wide temperature range, from just under 10°C and up to about 20°C. Aquatic species such as shrimp and catfish have a narrower range of optimum production at a higher temperature approaching 30°C. Trout and salmon; however, have a lower optimum temperature, no higher than 15°C.

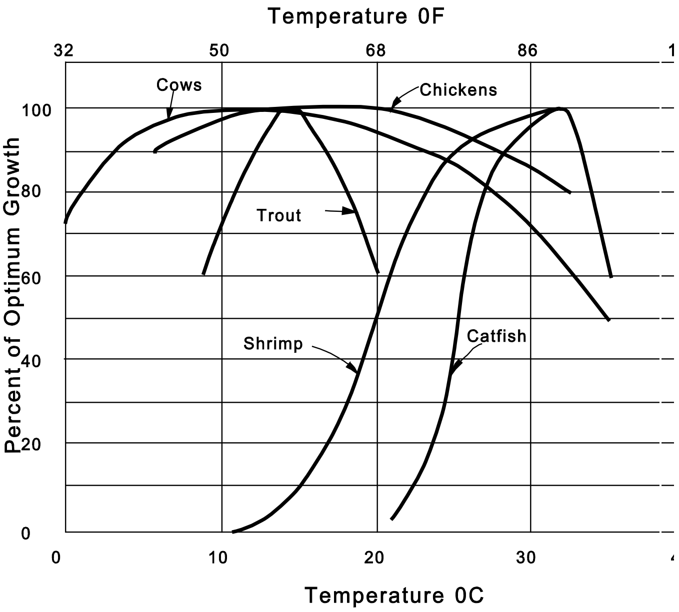

Figure 2: Optimum temperatures for growing selected animal and aquatic species.

Aquaculture pond and raceway heating is one of the most common uses of geothermal resources. Because of the significant heating requirements of these facilities and their ability to use low-temperature fluids (30°C and above), they are a natural application. This use of geothermal resources allows aquaculture operations to be sited in colder climates or closer to markets where conventional heating may not be economical. Geothermally heated aquaculture ponds are most common in the Imperial Valley of California (Rafferty, 1999), and geothermal water used in raceways are most common along the Snake River plain. There have been geothermal applications in place since the 1970s, and today there are at least 30 applications in 12 western states, and in over 15 countries, with the U.S. and China being the world leaders. In the United States almost 5,000 tonnes of Tilapia, catfish and bass are raised annually using geothermal water, with installations as far south as Louisiana, Mississippi, Alabama and Georgia. We calculate that it takes 0.242 TJ/yr/tonnes of fish using geothermal water in ponds and 0.675 TJ/yr/tonnes of fish in raceways (Lund and Freeston, 2001).

In the design of geothermally heated ponds and raceways, in order to determine the heat loss, it is necessary to first select the temperature at which the water must be maintained. Then, for a non-covered body of water, exposed to the elements, it exchanges heat with the atmosphere by way of four mechanisms: (1) evaporation, (2) convection, (3) radiation, and (4) conduction. These calculations are not covered in this paper, but can be found in Boyd and Rafferty (1998) or Rafferty (1998b).

2 United States Status

2.1 Greenhouses

The Geo-Heat Center has data on 37 greenhouse sites in the United States amounting to 43.8 ha and with an installed heating capacity of 119 MWt and annual energy use of 1132 TJ. The list of these installations is shown in Table 1.

Table 1. Geothermal greenhouse locations and energy data for the U.S.

State	# of Sites	Temp.	Capacity	Annual Energy		Area
		^{o}C	MWt	GWh/yr	TJ/yr	ha
CA	4	48-82	6.10	7.0	25.3	1.66
CO	1	71	0.47	2.1	7.6	0.20
ID	13	44-90	19.64	43.4	157.1	5.59
MT	4	43-66	5.01	18.0	64.5	1.61
NM	4	64-118	49.32	155.7	560.1	19.54
OR	4	42-104	3.41	8.6	31.4	1.22
SD	1	68	1.14	3.0	10.8	0.04
UT	5	88-95	33.79	75.8	272.7	13.45
WY	1	37	0.23	0.6	2.2	0.08
Total	37		119.11	314.2	1131.7	43.75

The best example of geothermally heated greenhouse development is in the state of New Mexico. Geothermal greenhousing accounts for more than half the greenhouse area in the state. In fact, New Mexico leads the U.S. in geothermal greenhouse development, and has the two largest in the U.S.: Burgetts Greenhouses and Masson Greenhouses located in the southwestern portion of the state. The success is due to several factors including good climate with abundant sunshine and low humidity, inexpensive and, collocation of geothermal resources with a supply of fresh water, a good agricultural labor force, and the availability of favorable shallow geothermal resources (well depths less than 300 m and resource temperature ranging from 62 to 116^{o}C). The other contributing factor is the stimulation provided by the New Mexico State University Geothermal Research Greenhouse and Aquaculture Center managed by the Southwest Technology Development Institute. This facility, leased to potential commercial developers, allows the client to determine if the greenhouse business is suitable for their investment. As a result, during the last 15 years, five clients have leased the facility, three as new business startups and two from out-of-state businesses interested in moving to New Mexico. All have since developed commercial operations elsewhere in the state (Witcher, 2002).

2.2 Aquaculture

The Geo-Heat Center has data on 45 aquaculture sites in the United States producing almost five million kg of fish annually. We also have some limited information on eight sites in the southeastern U.S. The total installed heating capacity is 129 MWt and the annual energy use is 2,795 TJ. The list of these installations is shown in Table 2.

Table 2. Geothermal aquaculture facility locations and energy data for the U.S.

State	# of Sites	Temp. Range	Capacity	Annual Energy	
		°C	MWt	GWh/yr	TJ/yr
AZ	4	27-41	19.04	66.8	240.0
CA	16	16-61	49.59	350.5	1260.2
CO	4	18-48	10.52	68.4	245.9
ID	9	32-38	26.64	186.7	671.8
MT	1	21	0.29	2.1	7.4
NM	1	85	1.17	8.2	29.5
NV	5	33-132	5.27	37.0	133.2
OR	2	82	2.34	16.4	59.0
SD	1	69	1.76	12.3	44.3
UT	1	52	11.72	24.0	86.4
WY	1	26	0.56	4.9	17.5
Total	45		128.90	777.3	2795.2

The largest increase in geothermal direct-use in the U.S. in the past five years has been in aquaculture pond and raceway heating. Ten new pond-heating projects were recently identified in the Imperial Valley of California along with the expansion of two existing projects (Rafferty, 1999). Approximately 3.66 million kg of Tilapia, catfish and hybrid striped bass are raised here annually. Most are shipped live to markets in Los Angeles and San Francisco. A second area identified as having a significant increase in aquaculture projects is along the Snake River Plain of southern Idaho. Seven new projects have been identified in this area, adding one million kg of Tilapia and catfish in annual production. These installations use cascaded water in raceways for raising their fish; whereas, in the Imperial Valley, ponds and tanks are most common. Fish from the Idaho sites are also shipped live to cities in Canada and northwestern U.S. An unusual development associated with one project in Idaho, is the introduction of alligators in the geothermal water to feed on the entrails from cleaning fish for market. The alligators solve the problem of waste disposal and also are marketed for their hides and meat (Clutter, 2002).

An additional eight sites have been reported in the southeastern U.S. using geothermal water in the 20 to 30°C range. In addition there are approximately four sites in Arizona raising Tilapia or shrimp and one in Montana raising white shrimp. This bring the total number of sites to 58 with an estimated capacity of 140 MWt and annual energy use of 3,000 TJ (833 GWh/yr).

3 Greenhouse and aquaculture information packages

In response to numerous requests for information from prospective developers of greenhouse or aquaculture projects using geothermal energy, the Geo-Heat Center prepared two comprehensive documents to assist these developers (Rafferty and Boyd, 1997; Boyd and Rafferty, 1998). The content of these two documents is outlined below:

The "Geothermal Greenhouse Information Package" is intended to provide a foundation of background information for developers of geothermal greenhouses. The material is divided into seven sections covering such issues as crop culture and prices, operating costs for greenhouses, heating system design, vendors and a list of other sources for information.

The "Aquaculture Information Package" is intended to provide background information to developers of geothermal aquaculture projects. The material is divided into eight sections and includes information on market and price information for typical species, aquaculture water quality issues, typical species culture information, pond heat loss calculations, an aquaculture glossary, regional and university aquaculture offices and state aquaculture permit requirements.

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Sustainable use of geothermal energy in Icelandic horticulture

Björn Gunnlaugsson, Magnus A. Agustsson and Sveinn Adalsteinsson
Icelandic Horticultural Centre, 810 Hveragerdi Iceland.
E-mail: bjorn@reykir.is, maa@bondi.is, sveinn@reykir.is

Abstract

The greenhouse industry in Iceland is based on abundant geothermal energy in form of steam or hot water. The annual use of geothermal energy in greenhouses is approx. 216 GWh/yr that accounts for 80% of the geothermal and hydroelectric energy used in horticulture. Other uses of geothermal energy are soil disinfection, 6 GWh/yr and soil heating in the cultivation of field vegetables, 15 GWh/yr. Artificial light has become an integral part of production in greenhouses to increase yield during the dark winter months. Cut flowers are now produced year-round with artificial light and this application is expected to increase substantially in vegetable production in the next decade. High-pressure sodium lamps, which are used for lighting, produce a lot of energy as heat that will partly substitute geothermal energy as a source for heating of the greenhouse, i.e. if no new lamp types will become available. Better cultivation techniques will also give more yield pr. m^2 resulting in a decreased greenhouse area. The estimated use of geothermal energy for heating greenhouses will therefore only be 114 GWh/yr in year 2011 that is approximately 60% of total geothermal and hydroelectric use in horticulture. No major changes in usage of geothermal energy for soil disinfection or soil heating in field vegetables are expected in this period. Soil heating in sports fields might increase in the next decade resulting in an annual use of 20 GWh/yr.

Keywords: *geothermal energy, greenhouse, horticulture, heating, disinfection, soil heating.*

1 Introduction

The first known experiments in Iceland with use of geothermal energy in horticulture date back to 1850 when potatoes were grown in naturally warm soil. In 1886 there are reports that open concrete ducts where used as a mean for soil warming in vegetable production to enhance growth (Hansson 1982). Soil heating has been used ever since to some extent, but it was not until in the 1970´s with the appearance of plastic materials that the systems for soil heating became economic and applicable for modern cultivation. Soil heating in field vegetable production is now applied on 12 ha and has not increased much for the past 10 years.

The greenhouse industry in Iceland, which dates back to 1924, has from the beginning been based on the utilisation of geothermal energy, mainly for heating greenhouses, but also to some extent for soil disinfection. Today the total greenhouse area is 18.5 ha (Table 1). More than 50 % of the area is used for vegetable production, 28% for cut flowers, 6% pot plants and 10 % for nursery stock and bedding plants.

Because of Iceland’s northerly altitude, global radiation in winter is way below minimum for plant growth. Even in summer extra light is needed to maintain high yields in vegetables. For the above reasons the use of artificial light is now an integral part of greenhouse production. Almost all growers of cut flowers use assimilation light in their production and in vegetable production there has been an increase is the use of artificial light. About 35% of the production area for vegetables is now installed with lights.

Table 1: The greenhouse area in Iceland 2003.

Cultures	Area, m^2	Area with artificial light, m^2	% artificial lights
Vegetables	97,093	34,161	35%
Cut flowers	52,788	50,754	96%
Pot plants	11,945	3,000	25%
Nursery stock, bedding plants	18,001		
Other uses	5,770		
Sum total	185,596	87,915	

Amenity horticulture is growing in Iceland and there are now 52 golf clubs with an estimate of 29 ha putting greens and over 50 full-size soccer fields for matches at an approximate size of 25 ha in total. Soil heating has been proposed to extend the playing season on these courses and it can be estimated that up to 6 ha of soccer fields and 10 ha of golf greens might be installed with soil heating apparatus in the next decade.

2 The utilisation of geothermal energy in Icelandic horticulture

Thin walled, welded steel pipes are used to emit heat into a greenhouse. Direct use of steam or hot water into the pipe system of the house is predominant although in some locations a heat exchanger has to be applied because of the corrosive nature of the steam/hot water. In order to maintain optimum temperatures the flow is controlled by a valve, which is normally situated at the end of the pipe system, equipped with a thermostat.

In recent years a change in cultivation technique has caused the energy use from geothermal sources to decrease. This is mainly due to the fact that year-round production with artificial light is now predominant in the flower sector and increasing in the cultivation of greenhouse vegetables. The lamps used to give the assimilation light emit a lot of heat, which substitutes the geothermal energy for heating. Higher productivity has also caused a decrease in greenhouse area thus demanding less energy for heating.

For soil disinfection three main methods are used. Where steam is available it is led under a tight plastic sheet, which is put over the beds and left running for 24 hrs, which is sufficient for adequate disinfection. Where only hot water is available an improved Hoddeston method (Johnson and Aas, 1960) is used where nozzles are put on a steel pipe to distribute the hot water over the soil. A simpler way for soil disinfection is to soak the soil thoroughly with 80-90°C hot water. The geothermal energy used for soil sterilisation has decreased in the past years due to increased use of inert growing media, which demand less hot water for sterilisation or even no sterilisation at all.

The main purpose of soil heating is to extend the growing season in order to be able to increase yield and to grow vegetable cultures and cultivars which otherwise would not be possible in the cool summer climate of Iceland. Soil temperatures in Iceland in summer rarely exceed 11°C but it is possible to maintain over 20°C with soil heating. In winter the soil normally freezes, forming a core of ice extending some 10-30 cm down into the soil profile. The ice-core prevents drainage of the soil in spring because it takes time for it to melt away and the soil gets waterlogged and cold. When soil heating is applied ice formation is prevented and soil preparations, planting or sowing can already take place in end of April. Losses from frost damage after planting or sowing in spring can also be diminished with soil heating, especially if applied together with fleece coverings. Soil heating of vegetable fields is predominantly applied for cultivation of carrots and cabbages, but also for leek, which is dependent on soil heating for normal growth.

A great increase in soil heating of vegetable fields was realised in the 1970's when improved techniques to install the heating systems was started, i.e. ploughing down PEL-pipes with a tractor. The heating grid is normally placed at a depth of 65-85 cm with 1-2 m spacing (Johannesdottir et al., 1986). The flow in controlled as to keep a temperature of 20-23°C in the soil. In some cases the heating is supplied by means of wastewater from greenhouses but a separate supply is more usual.

In recent years soil heating of soccer fields has been tried in 3 locations in Iceland with similar technique as for field vegetables. It can be expected that this application will increase in the coming years although it is not easy to predict how widespread this usage will be. Field experiments are now being run to investigate how the soil heating affects the design and maintenance of such fields.

3 The energy use in Icelandic horticulture

The three main uses of geothermal energy in horticultural production are greenhouse heating, soil disinfection and soil heating of vegetable and sports fields.

The major part of energy used in horticulture is to heat greenhouses, amounting to 88% of the total. Agustsson (1991) calculated the total energy use for heating of greenhouses to be 204 GWh/yr, on the basis of estimation from Orkusparnefnd (1987) that yearly energy use for greenhouses in Iceland is 1,200 kWh/m^2 (Table 2). In the next decade there was a 6% increase in the use of geothermal energy following an expansion of greenhouse area resulting in a total use of 216 GWh/yr in 2001.

Table 2: The energy use (GWh/yr) in horticulture 1991 and 2001. Estimation for 2011.

Use	**GWh/yr** **1991**	**2001**	**2011**
Heating of greenhouses	204	216	114
Soil heating in field vegetables	14	15	16
Soil disinfection	8	6	4
Amenity horticulture (soccer, golf)		2	20
Total geothermal energy	226	239	154
Artificial lighting	6	26	57
Other electricity use	2	3	3
Total energy use	234	268	214

Agustsson (1991), Gunnlaugsson and Agustsson (2001)

Until the year 2011 it is expected that the use of geothermal energy for greenhouse heating will decrease by almost 50% (Table 2). There are two reasons for this. Given that similar lamp technique will be used, increased use of artificial light in the production will make the contribution of geothermal energy used for heating less important because the lamps emit a lot of energy. This energy, which is in the form of heat, contributes directly to heating of the greenhouse and substitutes energy from geothermal sources. Secondly, higher productivity, especially as a consequence of increased use of artificial light, but better cultivation techniques in general will also lead to a decrease in greenhouse area and thus less energy use from geothermal sources.

Energy used for soil disinfection is only a minor part of the total energy used in horticulture and it will decrease in the coming years if the trend to use inert growing media continues.

Agustsson (1991) calculated the use of geothermal energy for soil heating in vegetable fields again based on estimation from Orkusparnefnd (1987). His calculations show the energy use to reach a soil temperature of 20-23°C is 130 $kWh/m^2/yr$. For 10.5 ha of heated vegetable fields in 1991 this gives a total of 14 GWh/yr or 6% of the total energy use in horticulture. The increase of this usage is approximately 6% in a 10-year period giving an estimate of total 16 GWh/yr in 2011.

To predict the need for geothermal energy to heat sports fields the same prerequisite is used as above for vegetable fields, i.e. 130 $kWh/m^2/yr$ to maintain optimum soil temperatures. Thus it is estimated that the use of geothermal energy in amenity horticulture will amount to 20 GWh/yr in year 2011 provided that in total 16 ha of sports fields will be heated.

4 Conclusions

The market for Icelandic horticultural products is limited to the domestic supply and has little opportunity to expand beyond that. A model to predict the energy use of horticulture in the future based on this fact therefore gives a distinct reduction of the use of geothermal energy in horticulture in the years to come. Only in amenity horticulture an increase is expected.

The competitiveness of Icelandic horticulture is poor and threatened by import of inexpensive horticultural products, mainly from S-Europe. If it is to survive in the future the productivity must increase and cost must go down. Electricity is one of the most important cost factors because of the extensive use for artificial light.

Alternative methods to produce electricity from geothermal sources by means of a thermoelectric generator may prove to be a tool to increase the competitiveness of Icelandic produced vegetable and ornamentals in future. It gives the possibility for decentralised production of electricity in the nurseries. The hot water could then firstly be used to generate electricity and secondly the effluent still contains enough energy for heating the greenhouse. If this method proves to be efficient geothermal energy may again gain its role as the most important source of energy in Icelandic horticulture.

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