JKAU: Eng. Sci., vol. 9, pp. 171-186 (1417 A.H./1997 A.D.)

Effect of Temperature on the Kinetics of Wastewater Disinfection Using Ultraviolet Radiation

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ABSTRACT. The effect of temperature on the performance and kinetics of the ultraviolet (UV) disinfection process was investigated using a single lamp annular UV reactor. The reactor was operated to disinfect secondary treated domestic wastewater at 10, 20, 30, 40 and 45°C. The first order rate model and the student t-test were used for data analysis. The effect of temperature in the normal operating range of most treatment plants, *i.e.*, 20 to 40°C, was found not to be statistically significant on the kinetics of the UV disinfection process. The kinetics of the UV disinfection process was highly affected by system operations at extreme temperatures, *i.e.*, at 10 and 45°C. In a temperature range of 20 to 40°C, the inactivation rate constant of fecal coliforms was about 590 cm^2/mW.sec. A relatively high inactivation rate constant of 770 cm^2/mW.sec was noted when the temperature of the disinfected wastewater was increased to 45°C. The inactivated rate constant at 10°C was relatively low at 350 cm^2/mW.sec. The minimum UV dose required to meet the MEPA fecal coliform standard of 200 organisms/100 ml, for effluent discharge, was about 180 mW.sec/cm^2.

1. Introduction

Increasing research on chlorination has revealed that residual chlorine imposes high toxicity to aquatic life, even at low concentrations, and leads to the formation of carcinogenic by-products[1-3]. The use of ultraviolet radiation in wastewater disinfection has received considerable attention as an emerging viable alternative to chlorination. The main advantages of the process are its effectiveness in killing viruses, the absence of harmful by-product, safety in handling and cost-effectiveness[4-6]

The main mechanism of inactivation by UV radiation is considered to be the dimerization of two pyrimidine molecules. When a cell is exposed to photons of UV light, new bonds, or diamers, are formed between two adjacent thymine monomers on the DNA (deoxyribonucleic acid) strands. The new bonds inhibit further replication of the cell and, consequently, cause its inactivation. However, some organisms have the ability to repair this damage by a series of enzymatic photochemical reactions[7,8]. Like other enzymatic reactions, the activity of the repair enzyme is expected to be influenced by temperature. It has been demonstrated[9] that the rate of bonds formation between adjacent thymine monomers on the DNA strand is faster at temperatures below 25°C than at higher temperatures. A similar study[7] has shown that the surviving fraction of Escherichia Coli. is higher at a temperature of 21°C than at lower temperatures. In contrast, some studies[10-12] have reported that UV disinfection is relatively insensitive to temperature change. However, most of these studies[10-12] were conducted on pure cultures which may not represent the actual case in wastewater treatment processes. Also, from the engineering aspect of the design of the ultraviolet disinfection reactors, the effect of temperature on the kinetics of the process needs to be addressed.

The main objective of this study was to investigate the effect of temperature on the kinetics of ultraviolet disinfection in secondary treated domestic wastewaters and to evaluate the success of the process in disinfecting high temperature wastewaters comparable to local wastewaters during summer months.

2. Material and Method

2.1 Design of Study

The main objective of this study was to demonstrate the effect of temperature of wastewater on the kinetics and performance of the disinfection process using ultraviolet radiation. To accomplish this objective, a laboratory scale single lamp annular UV reactor was operated to disinfect an unchlorinated seconuary treated domestic wastewater at 10, 20, 30, 40 and 45°C. The system was operated as a completely mixed batch reactor by circulating the content of the reactor at a high flow rate. The wastewater in the reactor was exposed to UV light for specific time in the range 5-40 seconds using a fused on/off switch. Influent and effluent samples were then collected and analyzed for fecal coliforms. All experiments were repeated four times to insure the validity and reproducability of the experimental data. However, only average values were used for process evaluation.

2.2 Experimental Set-up

To accomplish the objectives of the research, a single lamp annular UV reactor (Fig. 1) was built in the environmental engineering laboratories at King Abdulaziz University (KAU), Jeddah, Saudi Arabia. The reactor was constructed using a 5 cm inside diameter PVC pipe and 9.5 mm plexi-glass. An ultraviolet lamp was installed along the longitudinal axis of the reactor. The volume of the reactor, excluding the volume of the UV lamp was 500 cm^3. Technical and operational information for the lamp are listed in Table 1. The incident light intensity at the surface of the UV tube was calculated using the information shown in Table 1. The UV intensity was also measured using a Model J225 Blank-Ray Short Wave UV radiometer. The results obtained by the two methods were very comparable and showed a value about 9780 $\mu W/cm^2$. Since the normal operational time of the system was very short, in the order of seconds, temperature fluctuations were assumed negligible and thus, no quartz schealth or teflon tube was provided to the reactor.

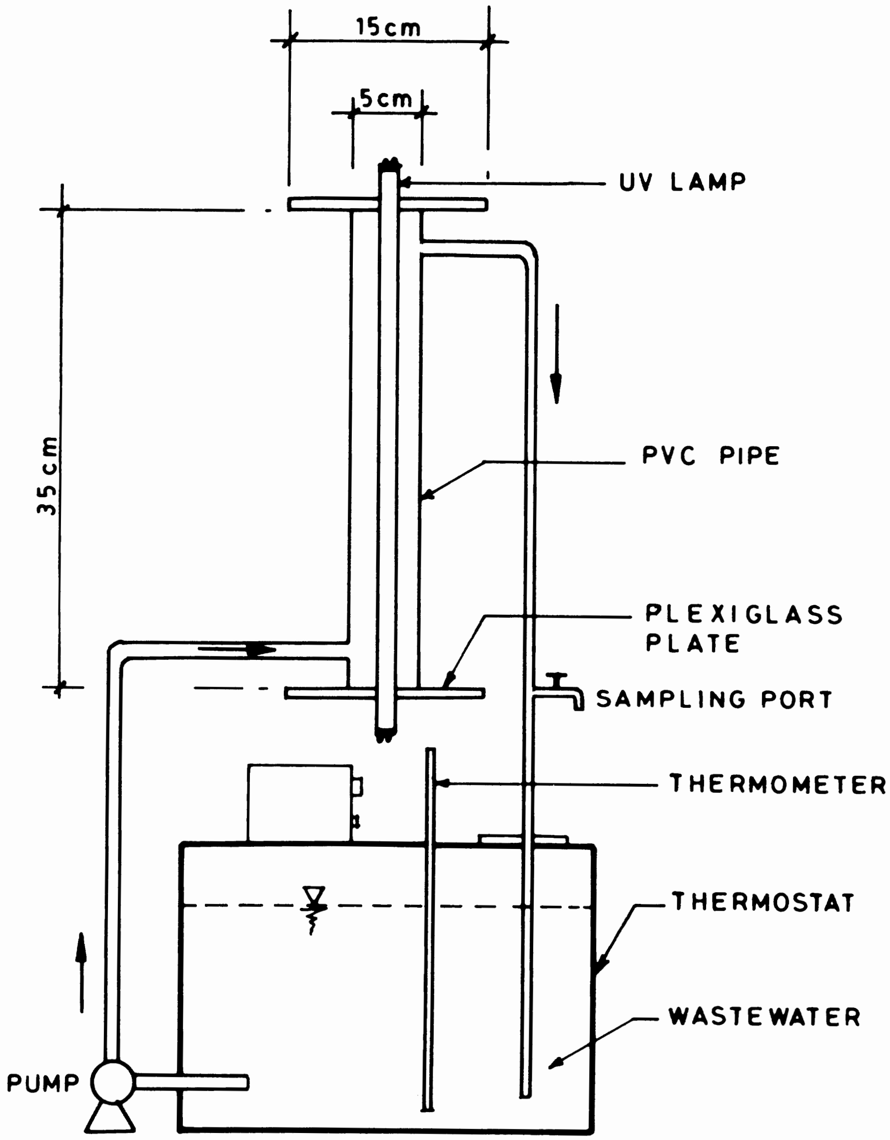

FIG. 1. Experimental laboratory scale single lamp annular UV reactor.

TABLE 1. UV lamp data.

Type	Philips TUV
Wave length, λ	254 nm
Power output at UV-254 nm, S	3.5 W
Lamp current	0.31 A
Irradiance at UV-254 nm	370 μW/m^2
Average useful life	3000 hours
Length of the tube, Y	43.8 cm
Tube diameter, D	26 mm
Base	Double pin
Ballast and starter	Same as for 20 W flourescent lamp

The wastewater in the reactor was circulated with the use of a cole-parmer 7553-50 Master-flex drive with a 7015-20 pump head. The temperature of the wastewater was controlled by using a Model T-1 Lavda thermostat equipped with an ET-31 Thermometer (W. Germany).

2.3 Influent Wastewater

The reactor was operated to disinfect unchlorinated and unfiltered wastewater obtained from the secondary effluent of a contact stabilization activated sludge, Al-Jamiah Treatment Plant, Jeddah. The secondary treated wastewater was pumped to the side of the reactor near the bottom and left the reactor near the top at the opposite side of the influent. Figure 2 shows the flow diagram of Al-Jamea contact stabilization activated sludge treatment plant and the location from which the secondary treated effluent was collected. About 10 liters of unchlorinated and unfiltered samples were collected daily from the plant and used as the feed to the UV reactor. The average characteristics of the secondary effluent of the plant are summarized in Table 2.

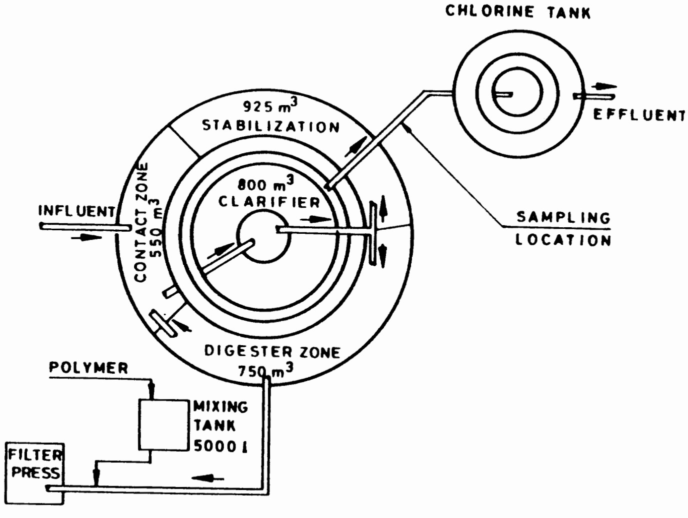

FIG. 2. Flow diagram of Al-Jamiah treatment plant.

TABLE 2. Characteristics of unchlorinated secondary effluent at Al-Jamiah district municipal treatment plant.

Parameter	Value*
pH	6.8 – 7.2 (7.2)
COD (mg/l)	85 – 110 (100)
TSS (mg/l)	5 – 35 (20)
Total coliforms (organism/100 ml)	$1 \times 10^6 - 1.6 \times 10^6$ (1.5×10^6)
Absorbance coefficient (cm^{-1})	0.39 – 0.42 (0.41)
Temperature (°C)	28 – 31 (29)

*Ranges and average values (between brackets) are given for 22 observations.

2.4 Reactor Operation

To quantify the kinetics of wastewater disinfection using UV radiation, a series of batch experiments were carried out. The procedure used was as follows. About 10 liters of unchlorinated secondary effluent was placed in a 15 liters thermostat. The temperature control nobe was set at the selected value and the thermostat was started. The wastewater in the thermostat was introduced to the bottom of the UV reactor using a positive displacement pump. The effluent from the UV reactor was circulated back to the thermostat. When the selected wastewater temperature was maintained, both the influent and effluent lines of the UV reactor were removed from the thermostat and then connected together. Thus, the UV reactor was operated as a completely mixed batch reactor. The wastewater in the UV reactor was then exposed to UV light for specific times of 5, 10, 15, 20, 30 and 40 seconds by the use of an on/off switch. Following each exposure, a wastewater sample was collected, from a sampling port located on the effluent line of the reactor, in a sterilized glass bottle and analyzed for fecal coliforms. A similar procedure was followed to estimate the bacterial density associated with particulates N_p. The N_p value was needed to quantify the kinetics of the process. The estimate of N_p requires generating data under high dose levels. Hence, in this experiment, the wastewater was exposed to UV radiation for a much longer time, *i.e.*, about 15 minutes, to ensure the inactivation of all microorganisms that were exposed to UV radiation. Only those which were incorporated in the particulates (N_p) will be measured in the disinfected sample.

2.5 Analytical Methods

Chemical oxygen demand (COD) was measured by using the dichromate reflux method outlined in Standard Methods for the Examination of Water and Wastewater (1980). The total coliform concentrations were measured by the membrane filter technique. All the glassware used was sterilized in a hot air oven at 170°C for two hours. The dilution bottles were filled with 100 ml of dilution water, and they were sterilized in an autoclave at 121°C by heating for 15 min. Filter holders were sterilized in a UV sterilizer by exposing them to UV light for at least three minutes. The procedure described in the Standard Methods (1980) for the determination of fecal coliforms by (membrane filter) MF technique was followed. The pH was measured by using a Model 230 A Fisher-Accument pH/ion meter. The UV absorbance coefficient was determined in filtered samples directly by using a spectronic 21 UVD spectrophotometer at 254 nm wavelength. Filtered samples were obtained by passing samples through 0.45 μm membrane filters.

2.6 Data Analysis

The first order rate model was used for data analysis. The inactivation rate constants of fecal coliforms obtained at various temperatures of the influent wastewater were compared by plotting the UV dose versus the logarithm of survival ratio. This was done to evaluate the effect of temperature of wastewater on the kinetics of bacterial die-off rate. Statistical analyses were made using the student t-test at a 5 percent significance level to determine whether differences existed between the experimental results obtained at various operating temperatures. The UV dose was calculated by multiplying average UV intensity inside the reactor by the exposure time of wastewater to UV radiation. The average UV radiation in the reactor was determined by using the point source summation (PSS) method (finite line source). A separate discussion of the PSS method is presented to demonstrate its application in the present study.

2.7 Average UV Intensity

The point source summation method was used in the present study to estimate the average UV intensity in the reactor. This method was first applied to UV disifection by Qualls and Johnson[2]. In this method, it is assumed that the lamp comprises a finite series of point sources that emit energy radially in all directions. The UV intensity at any point within the reactor volume will be the total intensities provided by all designated point sources. As the intensity provided by any point source moves away from the source, the intensity will attenuate by the dissipation and absorption mechanisms. The dissipation mechanism is the dilution of the energy as a result of increase in the surface area on which the energy is being projected. The dissipation mechanism is described by the equation

$$I = S/(4 \pi R^2) \tag{1}$$

where,

I = intensity at distance R from the source, $\mu W/cm^2$

S = power at source, μW

R = distance from the source, cm

The absorption mechanism is due to the energy demand of the medium through which UV light is transmitted. The light transmission is related to the absorptive properties of the medium. The absorption mechanism is described by Beer's law

$$I = I_o \exp [- \alpha R] \tag{2}$$

where,

I_o = intensity at the source, $\mu W/cm^2$

α = absorbance coefficient of the medium, cm^{-1}

R = distance between the source and point of interest, cm

Intensity I in Equation 1 is substituted for I_o in Equation 2 to include both the dissipation and the absorption mechanisms

$$I = S/(4 \pi R^2) \exp (- \alpha R)$$

Thus, the intensity at any point, or receiver location, will be the summation of the intensities from each point source :

$$I_p = \sum_{n=1}^{n=N} \frac{S/N^*}{4 \pi R^2} \exp [- \alpha R] \tag{3}$$

I_p = intensity at point p, $\mu W/cm^2$

N^* = number of point sources

To apply the PSS method to the present study, the UV lamp was assumed to be divided into 50 elements and every element was considered a point source. A grid system with a size of 12 × 35 was assumed in the cross-sectional area of the reactor; thus 420 equally spaced receivers were assumed. The intensity at each receiver, which is the total intensity from all designated point sources, was calculated using Equation 3. The average UV intensity in the reactor was determined by dividing the sum of intensities at all receivers by the number of receivers.

To facilitate the calculation a computer program for solution of Equation 3 was developed, as illustrated by Fig. 3. More detailed information on the point source summation method can be obtained elsewhere[2].

3. Results and Discussion

3.1 Effect of Temperature on Process Kinetics

The UV disinfection process is usually described by a first order expression with respect to both surviving organisms and intensity of UV light[6,9].

$$N = N_o \exp (- kIT) \tag{4}$$

where,

N = the remaining bacterial density after UV exposure, organisms/100 ml

N_o = the initial bacterial density, organisms/100

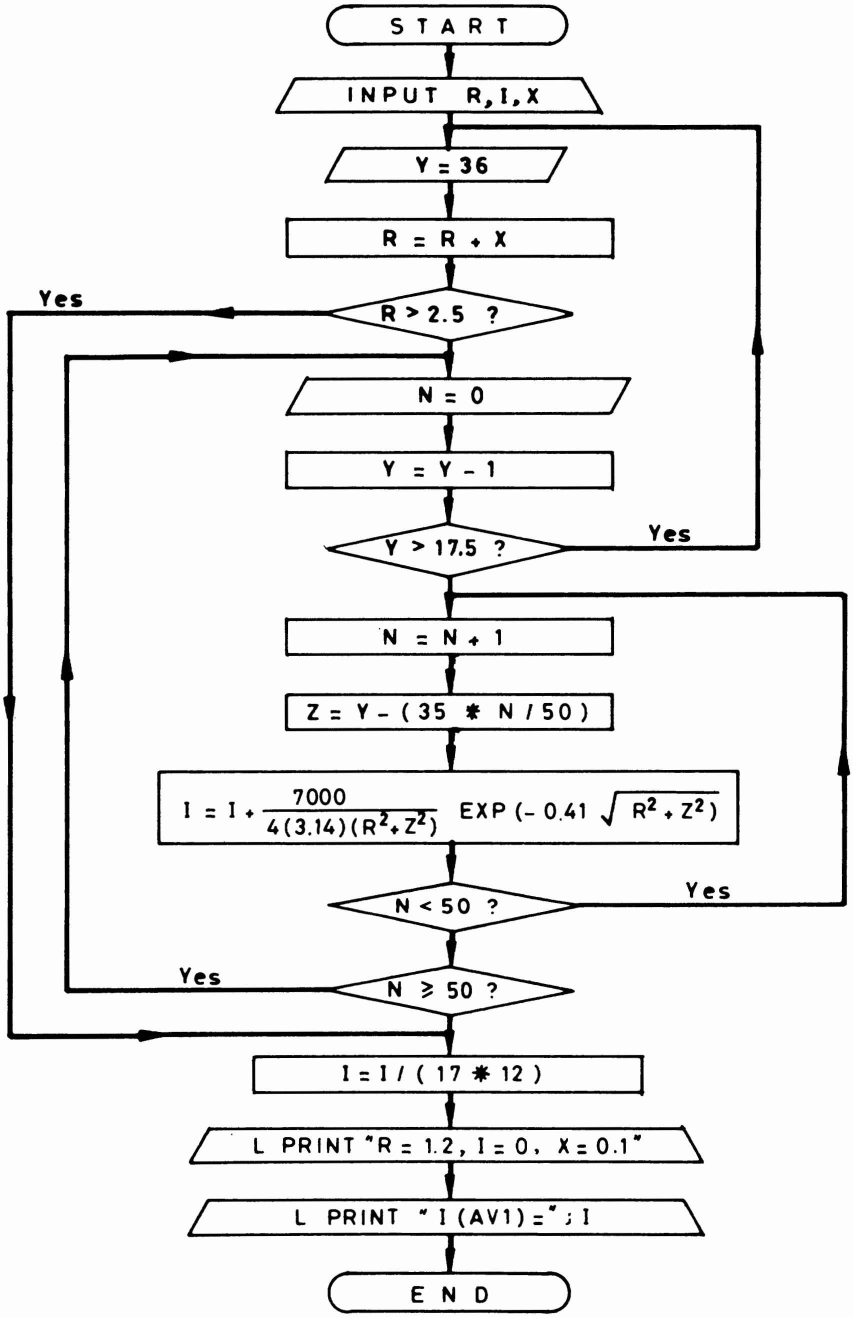

FIG. 3. Estimation of average UV intensity using the PPS method. (Conditions: 35 cm height of reactor (Y), 1.3 radius of tube (R), 0.1 cm horizontal distances between grid lines (X), 1 cm length of each increment along the axial of UV tube (Y), 50 number of point sources (N), 3.5 watt power output (S).

k = inactivation rate constant, $cm^2/\mu W.sec$

I = UV intensity, $\mu W/cm^2$

T = time of exposure, sec

Studies on wastewater disinfection using UV radiation have shown a residual density of coliform bacteria even with increased UV dosage. This has been attributed to the incorporation of bacteria in particular matter and consequently being unexposed to UV light[5,11]. Thus the above equation was modified to account for the unaffected bateria by UV radiation[6] :

$$N = N_o \exp(-kIT) + N_p \tag{5}$$

where,

N_p = bacterial density associated with the particulates, organism/100 ml

The above modified expression excluded the effect of the bacterial density N_p on the initial bacterial density N_o which will give low estimates of K values. Thus, the above expression is further modified to the following

$$N = (N_o - N_p) \exp(-kIT) + N_p \tag{6}$$

The above equation shows that when the fraction survival $(N - N_p)/(N_o - N_p)$ is plotted against the UV dose IT, a linear relationship can be obtained with a slope representing the bacterial inactivation rate constant k. As discussed before, the N_p value was determined by exposing the wastewater to UV light for a long period of time. This was done for wastewaters at various temperatures. As shown in Fig. 4, no correlation was observed between the temperature of the wastewater and the bacterial density associated with particulates N_p. However, the N_p values have been found to correlate to SS concentrations by a power type expression[13]

$$N_p = c\ SS^m$$

where c and m are coefficients specific to a given wastewater reflecting the level at which microorganism are incorporated in the particulates. To investigate the possible correlation between SS and N_p, the N_p values were determined for various wastewater samples having a wide range of suspended solids concentration (50-380 mg/l). The suspended solids concentrations were increased by the additions of specific amounts of mixed liquor suspended solids obtained from the contact tank to the original samples. A remarkable linearity was observed (Fig. 5) when the log N_p was plotted against the logarithm of the suspended solids concentration. The following relationship was obtained with a coefficient of determination $R^2 = 0.975$:

$$N_p = 1.81\ SS^{0.61} \tag{7}$$

A similar equation, demonstrating power relationship between the particulate density N_p and the suspended solids concentration SS, has been reported by others[4,6]. The average UV intensity in the reactor was 4500 $\mu W/cm^2$, estimated by using the PSS method.

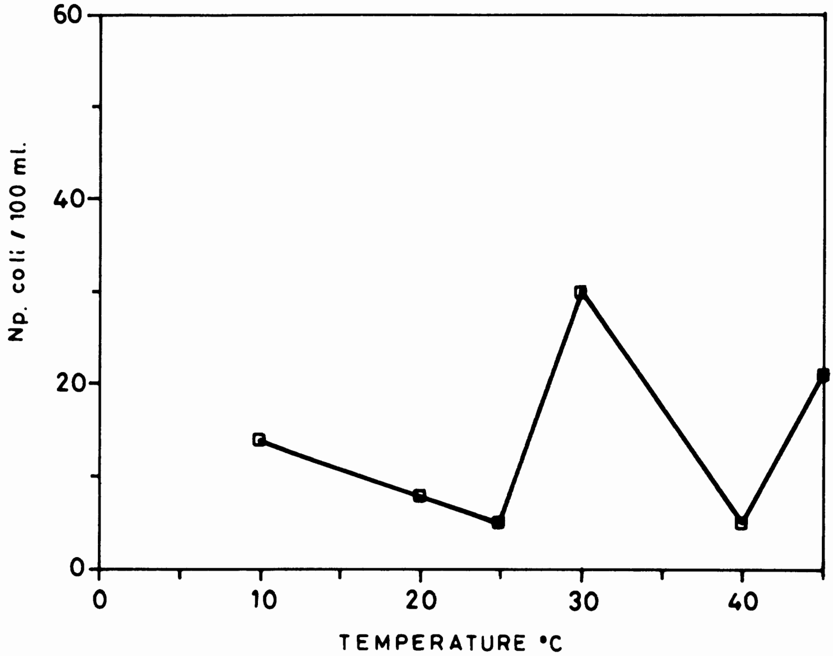

FIG. 4. Effect of temperature on the coliform density associated with particulates.

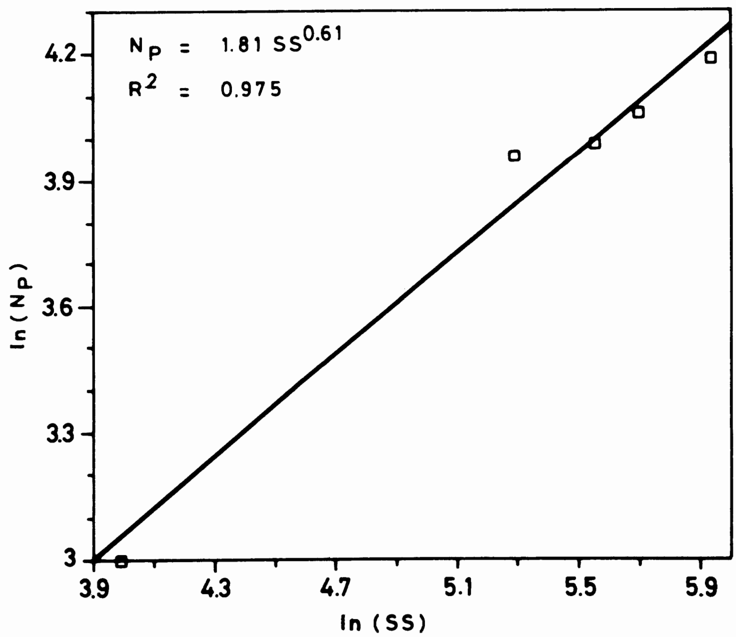

FIG. 5. Correlation between suspended solids concentration and the coliform density associated with particulates.

Figure 6 shows plots of UV doses against the logarithm of survival fractions of fecal coliforms at various temperatures of the disinfected wastewater. As shown in the figure, linear relationships existed with coefficients of determination in the range 0.80 to 0.98. The inactivation rate constants obtained at temperatures 10, 20, 30, 40 and 45°C were 3.51, 5.83, 5.90, 5.92 and 7.71 $\times 10^{-5}$ $cm^2/\mu W.sec$ respectively.

Under normal operation conditions, *i.e.*, 20-40°C, the inactivation rate constant was not affected by the temperature of the disinfected wastewater. Within this temperature range, the inactivation rate constant was about 590 $cm^2/mW.sec$. However, a low inactivation rate constant of 350 $cm^2/mW.sec$ was observed when the operating temperature was reduced to 10°C. In contrast, a considerable increase in the bacterial inactivation rate constant, of 770 $cm^2/mW.sec$, was noted when the system was operated to disinfect wastewater at 45°C. Thus, the inactivation rate constant showed more than two times increase when the operating wastewater temperature was increased by 4.5 folds. The observed appreciable increase in the bacterial inactivation rate constant at 45°C might be explained by the decrease in the rate of repair enzyme activity as enzyme denaturation occurs at elevated temperatures.

Figure 6 also shows the required UV dose, calculated as the product of contact time times the average UV intensity in the reactor, *i.e.*, 4500 mW/cm^2, to achieve a fecal coliform inactivation of 4 logs (99.99% reduction). The required UV doses to achieve a 99.99% inactivation of fecal coliform at wastewater temperature of 10, 20, 30, 40 and 45°C were 70, 54, 54, 60 and 42 $mW.sec/cm^2$ respectively. Thus, under normal operating temperature of most treatment plants, *i.e.*, 20-40°C, the required UV dose to achieve 99.99% is independent of temperature change. However, at a low operating temperature of 10°C higher UV dose of 70 $mW.sec/cm^2$ was required to obtain similar efficiency.

It is clear from Fig. 7 that the effect of changes in the temperature of the disinfected wastewater within the range 20-40°C on the kinetics of the process was not remarkable. Hence, the student t-test was used at the 5 percent significance level to compare data obtained at the temperature range of 20-40°C with experimental results obtained at constant temperature operations. It was found that the difference between the two means was not statistically significant, *i.e.*, the temperature variations within the range 20-40°C had no effect on the kinetics of the UV disinfection process. However, a considerable increase in the inactivation rate constant was noted when the temperature of the disinfected wastewater was increased to 45°C. A relatively low inactivation rate constant was found when the temperature of the disinfected wastewater was reduced to 10°C. However, as 10 and 45°C are outside the operating range of most treatment plants, it is reasonable to assume that the effect of temperature change on the kinetics of UV disinfection process is negligible.

The results of batch disinfection using UV radiation obtained at the normal operating temperature of 20-40°C are summarized in Fig. 8. The remaining fecal coliform concentrations measured after the exposure to UV radiation at doses of 90, 130, and 280 $mW.sec/cm^2$, which correspond to contact times of 20, 30 and 40 seconds respectively, are plotted in the figure. The observed differences in the effluent

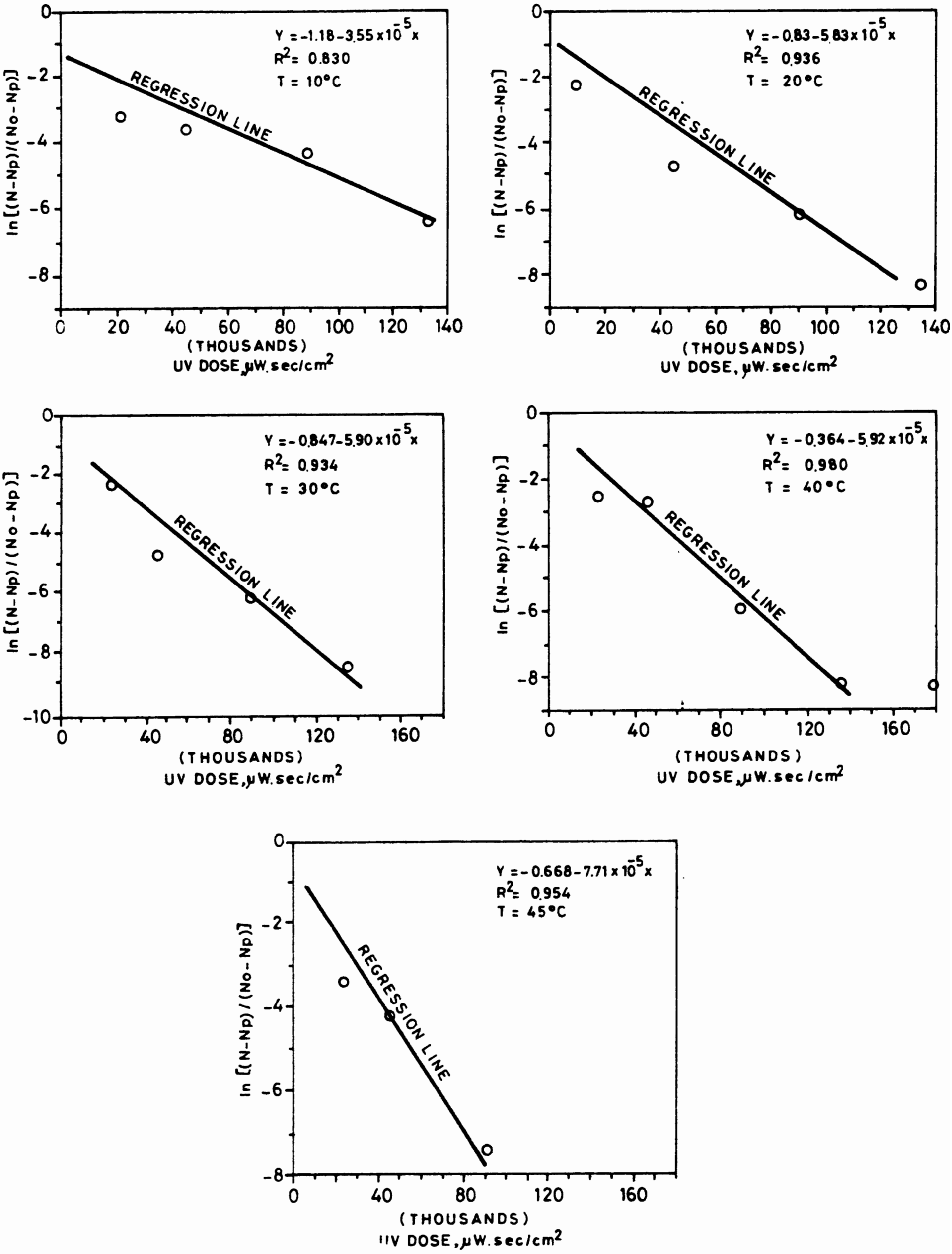

FIG. 6. Correlation between survival fraction and UV dose at various wastewater temperatures.

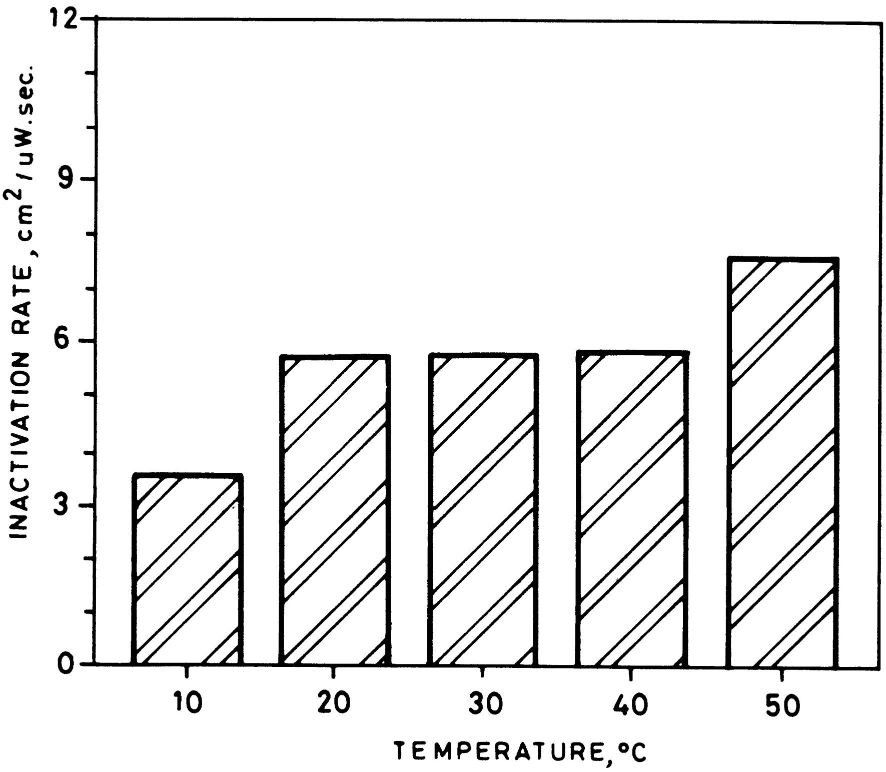

FIG. 7. Effect of wastewater temperature on the bacterial inactivation rate constant.

fecal coliform concentrations, obtained at various operating temperature are mainly due to the variations in the influent fecal coliform concentrations. However, the inactivation rate of fecal coliforms was not affected by the change in wastewater temperature, within that range, as discussed before. In Fig. 8 the upper boundary of the experimental data was indicated by a solid line. By extending a horizontal line at a fecal coliform concentration of 200 coliforms/100 ml, the abcissa reading is about 180 mW.sec/cm^2. Thus the required UV dose to meet the standard for effluent discharge to coastal waters set by the Meteorology and Environmental Protection Administration (MEA) is about 180 mw.sec/cm^2.

3.2 Engineering Application

The effect of temperature on the kinetics and performance of the UV disinfection process needs to be investigated for local application of this process. Wastewater temperatures as high as 35 to 40°C are measured at KAU treatment plant during summer months, which must be considered for process design and also in evaluating UV disinfection as an alternative to chlorination. The use of high temperature desalinated drinking water and the hot climate during summer months are the main causes of the observed high wastewater temperature in the city of Jeddah.

The present study has demonstrated that the kinetics of the process is not sensitive

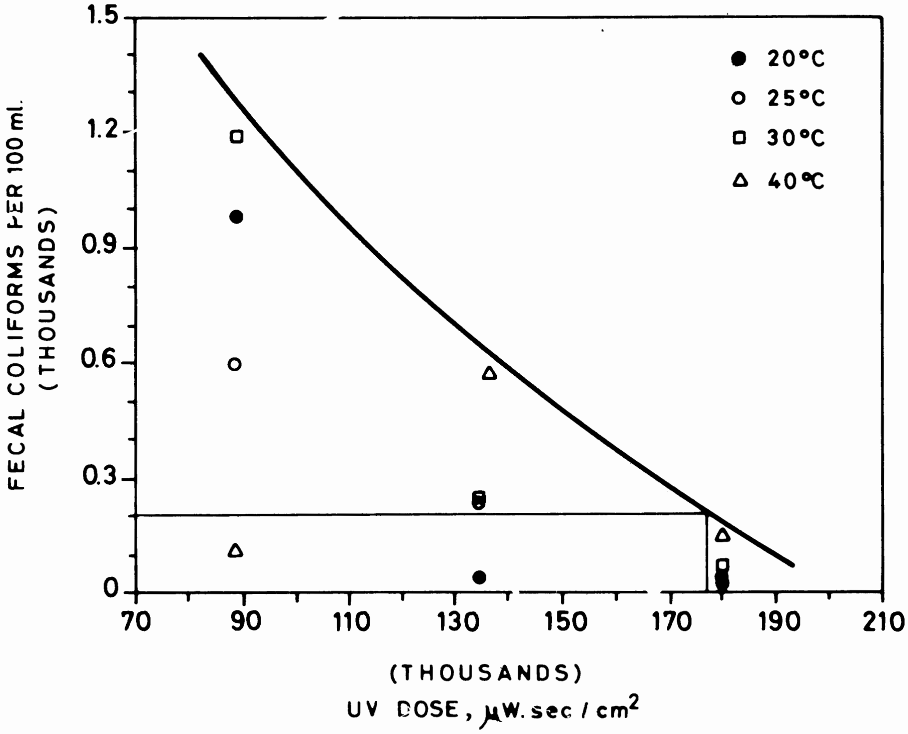

FIG. 8. UV dose versus effluent fecal coliforms concentration.

to temperature change in the range 20-40°C. This can be considered an advantage when considering local use of UV disinfection process. Based on the study the minimum required UV dose to meet local standards of 200 organisms/100 ml of fecal coliforms was about 180 mW.sec/cm^2, at a temperature range of 20-40°C. It was also noted that the inactivation rate constant, in this temperature range, is about 600 cm^2/mW.sec., which is needed for process design.

4. Conclusion

Temperature in the range 20-40°C has no effect on the kinetics of wastewater disinfection using UV radiation. An inactivation rate costant of 350 cm^2/mW.sec was found at a temperature of 10°C, 770 cm^2/mw.sec was observed at 45°C, as compared with a value of 583-592 cm^2/mW.sec at temperatures in the range 20-40°C. Between 20 to 40°C, the average UV dose required to achieve 99.99% reduction of the influent fecal coliforms was in the range 54 to 60 mW.sec/cm^2. At an operating temperature of 10°C the average required UV dose to achieve 99.99% inactivation was as high as 70 mW.sec/cm^2. A low UV dose of 42 mW.sec/cm^2 was needed at 45°C to obtain 99.99% inactivation of influent fecal coliforms. For local application of the process, the required UV dose to meet MEPA standards for wastewater discharge was 180 mW.sec/cm^2.

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تأثير الحرارة على حركية تطهير المياه الملوثة باستخدام الأشعة فوق البنفسجية

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المستخلص . تمت دراسة تأثير درجة حرارة المياه المعالجة على حركية وكفاءة عملية التطهير باستخدام الأشعة فوق البنفسجية . ولتحقيق أهداف البحث تم بناء وتشغيل مفاعل مركزي مزود بمصدر للأشعة فوق البنفسجية لتطهير نواتج محطات معالجة مياه الصرف الصحي عند درجات حرارة ١٠ ، ٢٠ ، ٣٠ ، ٤٠ و ٤٥°م .

ولقد دلت نتائج هذه الدراسة على أن التغير في درجة حرارة المياه المعالجة في حالات التشغيل العادية أي من ٢٠ إلى ٤٠°م لا يؤثر على حركية عملية التطهير باستخدام الأشعة فوق البنفسجية . أما عند تشغيل المفاعل لتطهير المياه المعالجة عند درجتي حرارة ١٠ و ٤٥°م ، فلقد لوحظ تأثير كبير على حركية التطهير . كما بلغ عامل تلاشي البكتيريا ٥٩٠ سم^{٢}/ملي وات . ثانية عند درجة تتراوح من ٢٠ إلى ٤٠°م . وقد لوحظ ارتفاع في قيمة عامل تلاشي البكتيريا إلى ٧٧٠ سم^{٢}/ملي وات . ثانية عند زيادة درجة الحرارة إلى ٤٥°م . أما قيمة تلاشي البكتيريا عند درجة حرارة ١٠°م فكانت منخفضة نسبيًا ، حيث بلغت قيمتها ٣٥٠ سم^{٢}/ملي وات . ثانية .

كما دلت الدراسة أن ١٨٠ ملي وات ثانية/سم^{٢} هي أقل جرعة لازمة من الأشعة فوق البنفسجية للحصول على تركيز للبكتيريا ٢٠٠/١٠٠ ملي في المياه المعالجة ، وهو الحد المسموح به من قبل معايير مصلحة الأرصاد وحماية البيئة لمياه الصرف الصحي المعالجة .