Feasibility assessment of application of onsite volume reduction system for source-separated urine

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Abstract: The onsite volume reduction system (OVRS) is a newly developed drying method for volume reduction of source-separated urine. The OVRS is aimed for nutrient recovery in concentrated urine, which then can be applied at farmland as natural fertilizer, saving significant transportation cost. This study was carried out to assess whether the OVRS can be applied effectively with small size in various climate conditions. The results of laboratory scale experiments revealed inter-relationship between Reynolds and Sherwood Numbers, which was used to evaluate mass transfer coefficient and evaporation rate based on climate data. Using the climate data and established experimental data, size of vertical drying sheet was estimated following the set design procedures. The estimation based on a household comprising ten family members showed that for 80% volume reduction per day the small size of 2396~7487, 4177 ~ 9999, 4315~26806 and 10887~90768 cm^2 of vertical sheet is required if the OVRS is installed in dry, tropical, temperate and continental climates. Therefore, OVRS is quite feasible for the above mentioned climate conditions.

Keywords: source-separation, volume reduction, drying rate, effective drying area.

INTRODUCTION:

We have proposed onsite volume reduction system (OVRS) for drying of source-separated human urine with application of atmospheric energy. This system was developed to minimize transportation cost of human urine from household to farmland to be applied as natural fertilizer. Masoom (et al, 2009) evaluated the transportation cost of human urine from household to farmland and compared it with cost of commercially available fertilizer for paddy field in Southern Pakistan. The estimation revealed that transportation cost of raw human urine was higher than the cost of commercial fertilizer for the farmland located at 30-40 km away from human settlements. To resolve this issue, 65% volume reduction of urine was required to meet the cost of commercially available fertilizer. However, higher volume reduction of about 80% was proposed to provide financial incentives to farmers to use urine instead of commercially available fertilizer.

Various volume reduction methods such as reverse osmosis, electro dialysis, freezing and thawing and conventional heating etc. have been tried previously, however, these processes are energy and cost intensive. Therefore, the OVRS which is comprised of vertical sheet whose bottom end is in contact with urine tank was tried at laboratory scale. In this method, water penetrates into the vertical sheet under capillary pressure, to evaporate into the atmosphere. The evaporation rate of water in the OVRS is affected by air temperature, air humidity, wind velocity size of vertical sheet and cloth sheet properties etc. Our previous findings have shown the relationship among these factors. The aim of this paper is to estimate the required size vertical sheet for design of OVRS at household for various climate regions with natural atmospheric conditions. It is considered that OVRS can treat urine from household of 10 family members which can generate 10 liters of urine everyday. The target amount of urine to be evaporated is 8 liters to achieve 80% volume reduction.

METHOD

The performance of the OVRS was evaluated at laboratory scale experiment as a result of which a following inter-relationship between Sherwood (*Sh*) and Reynolds (*Re*) Numbers was found using de-ionized water as a model of urine.

$$Sh = 0.08Re^{0.266} \qquad (1)$$

The above equation was used for estimation of mass transfer coefficient and evaporation rate using climate data based on which the dimensions of vertical drying sheet were measured. The design procedures for estimation of vertical sheet which is as discussed as under:

As the performance of OVRS is based on combination of air temperature, humidity and air flow rate, therefore, monthly average air temperature and humidity respectively for various climate regions, shown in the Tables 2 and 3, were collected. The dry, tropical, temperate and continental climate regions were considered as the OVRS is expected to produce the desired performance in those conditions. However, polar climate was not taken into consideration due to the fact that the system may not perform well with the desired efficiency under extreme weather conditions of negative air temperature around the year. The step-wise detailed methodology for this assessment is explained in the Figure 1.

To make the task easier, we selected each city to represent each of the climate zones. The climate regions along with the corresponding cities are given in the Table 1 with highlighted four cities of Miami, Jacobabad, Los Angeles and Seoul were selected for evaluation.

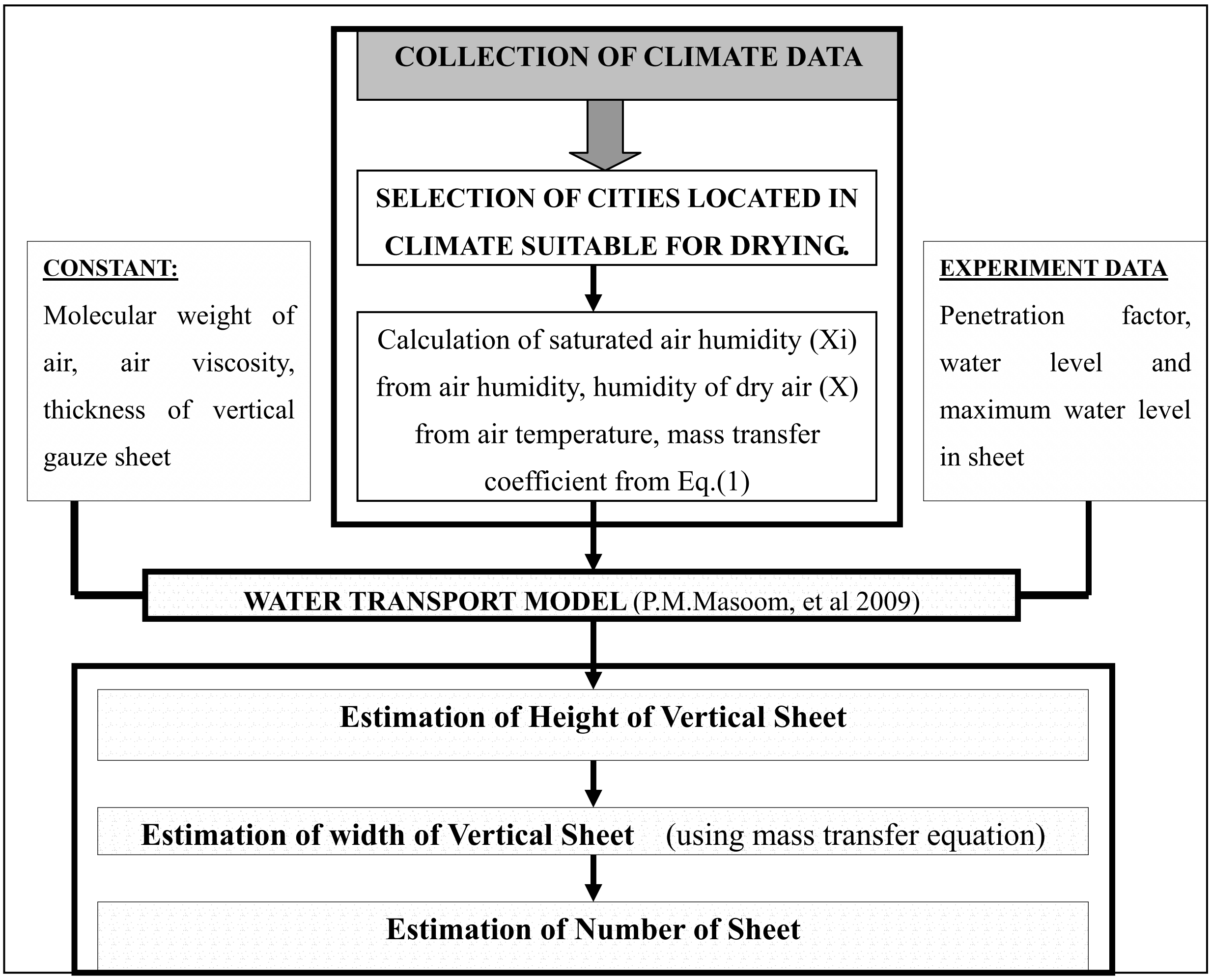

Figure1: Flow diagram indicating the entire procedure for estimation of the dimension of vertical sheet.

Table 1: Selected Climate Regions and corresponding cities.

Climate Zone	Sub regions of Climate	City/Country/Territory
Tropical Climate	Topical Rainforest Climate (*Af*)	Singapore
	Tropical Monsoon Climate (*Am)*	Miami, USA
	Tropical wet and dry or savanna climate (*Aw)*	Bangalore, India
Dry Climate	Dry Climate (*Bw*)	Jacobabad, Pakistan
Temperate Climate	Mediterranean Climate (*Cfb)*	Los Angeles, USA
	Humid Tropical Climate (*Cfa)*	Houston, USA
	Maritime temperate or oceanic climate (*Cwb)*	Mexico city, Mexico
Continental Climate	Hot Summer Continental Climate (*Dwa*)	Seoul, South Korea
	Warm summer continental climate(*Dfa)*	Stockholm, Sweden

Table 2: Monthly recorded average (high and low) air temperature data for selected cities

(Reference: web page www.istc.org)

City	Month		JA	FB	MR	AP	MY	JU	JL	AG	SP.	OC	NO	DEC
Singapore	Average Monthly air temperature (-C)	Low	23	23	24	24	24	24	24	24	24	23	23	23
(Af)		High	30	31	31	31	32	31	31	31	31	31	31	31
Miami		Low	**16**	**16**	**18**	**19**	22	23	24	24	24	22	**19**	**17**
(Am)		High	**23**	**24**	**26**	**27**	29	30	31	31	31	28	**26**	**24**
Bangalore		Low	16	17	19	21	21	20	20	19	19	19	17	16
(Aw)		High	27	30	32	33	32	29	27	27	28	27	27	26
JCD.		Low	**7**	**9**	**16**	22	26	29	30	28	24	19	**12**	**7**
(Bw)		High	**23**	**25**	**33**	39	44	46	43	40	39	37	**31**	**24**
LA.		Low	**8**	**8**	**9**	**10**	12	13	16	16	14	12	**10**	**8**
(Cfb)		High	**18**	19	19	21	22	24	27	28	27	24	23	19
Houston		Low	7	8	12	16	19	22	23	23	21	16	11	7
(Cfa)		High	17	18	22	26	29	32	33	34	31	27	22	17
Mexico		Low	6	6	8	11	12	13	12	12	12	10	8	6
(Cwb)		High	19	21	24	25	26	24	23	23	23	21	20	19
Seoul		Low	**-9**	**-7**	**-2**	**5**	11	16	21	22	15	7	**0**	**-7**
(Dwa)		High	**0**	**3**	**8**	**17**	22	27	29	31	26	19	**11**	**3**
Stockholm		Low	-5	-5	-4	7	9	11	14	13	9	3	1	-2
(Dfa)		High	-1	-1	3	8	14	19	22	20	15	9	5	2

JA = January, FB = February, MR = March, AP = April, MY = May, JU =June, JL=July, AG = August, SP= September, OC=October and DEC = December, JCD= Jacobabad (South Pakistan), LA= Los Angeles.

12 hour operation of OVRS during day or night times is considered. For estimation the lowest values of air temperature and the highest values for air humidity as highlighted in the Tables 2 and 3 respectively were selected for each city and is shown in Table 4 which is for estimation. Although estimation is carried out for various wind velocities from 1 to 6 m/sec, however, required wind velocity for OVRS was set to 2 m/sec. Treatment of 8000 gram of urine from 10 family members is considered every day. The procedure for calculation of dimensions of vertical sheet is explained as under:

The drying process is based on balance of water supply to the sheet and evaporation through the sheet surface (Masoom, et al 2009), which can be explained in below equation:

$$Accumulation = Water\ Sypply - Water\ \ Evaporation \ \ldots..(2)$$

Table 3: Monthly recorded average high and low air humidity data for selected cities.

(Reference: web page www.istc.org)

City	Month		JA	FB	MR	AP	MY	JU	JL	AG	SP	OC	NO	DE
Singapore	Monthly Average Air Humidity (%)	Low	78	71	70	74	73	73	72	72	72	72	75	78
(Af)		High	82	77	76	77	79	79	79	78	79	78	79	82
Miami		Low	66	63	62	64	**69**	**68**	**68**	**68**	**70**	**69**	64	65
(Am)		High	**81**	**82**	77	73	75	75	75	76	**79**	**80**	**77**	**82**
Bangalore		Low	**70**	**73**	**65**	60	**61**	60	56	52	54	59	**65**	**62**
(Aw)		High	74	78	72	68	67	67	62	59	57	61	65	64
Jacobabad		Low	**34**	**35**	31	30	27	**31**	**42**	**49**	**40**	31	29	31
(Bw)		High	**65**	54	45	41	43	**57**	**65**	**71**	**68**	56	57	**63**
LA		Low	47	53	51	**55**	**59**	**58**	**55**	**54**	**52**	49	38	44
(Cfb)		High	67	74	77	**82**	**86**	**87**	**88**	**87**	**82**	75	62	60
Houston		Low	66	61	59	59	60	60	57	54	58	54	58	64
(Cfa)		High	85	85	84	86	87	87	88	88	88	86	84	84
Mexico		Low	34	28	26	29	29	48	50	50	54	47	41	37
(Cwb)		High	79	72	68	66	69	82	84	85	86	83	82	81
Seoul		Low	51	47	46	46	51	**54**	**67**	**62**	**55**	48	**52**	**52**
(Dwa)		High	78	77	77	83	**87**	**87**	**91**	**90**	**89**	**88**	83	79
Stockholm		Low	83	77	68	60	53	55	59	64	69	76	85	86
(Dfa)		High	85	83	82	76	66	68	74	81	87	88	89	88

LA = Los Angeles.

Masoom (et al, 2009) developed following water transport model based on equation (2) for calculation of the height of vertical drying sheet.

$$WT\frac{dH}{dt} = [(\frac{\sigma}{\mu})(\frac{H_{max} - H}{H})(WT)] - [(M_{air} Ky(Xi - X)(WH)] \quad (3)$$

where T and W are thickness and width of vertical sheet (cm), σ is penetration factor (g / cm sec^2), μ is viscosity (g / cm sec), H_{max} is maximum height of sheet (cm), H is sheet height (cm), $M_{(air)}$ is molecular weight of air (g / kmol), Ky is mass transfer coefficient (kmol / cm^2 hr), Xi is saturated air humidity (g - water / g - dry air) and X is humidity of air (g - water/ g - dry air).

For resolving the above mentioned model, the values of 1.0×10^{-5} g/cm sec^2 and 31 cm respectively established through experimental work for penetration factor and H_{max} were used for gauze vertical sheet. Ky, μ, Xi, X can be calculated from climate conditions. Sheet width (W) was estimated by using following equation.

$$q_{evaporation} = M_{air} Ky(Xi - X)(WH) \quad (4)$$

where q evaporation is quantity of volume to be treated per day.

Table 4 Selected data of average lowest air temperature and average the highest air humidity for estimation.

City/ Climate Region	Level	6 selected values as highlighted in Tables 2 and 3 for 4 cities.													
		Air Temperature(-C)							Air Humidity (%)						
	Points	1	2	3	4	5	6	Avg.	1	2	3	4	5	6	Avg.
Miami	Low	16	16	18	19	19	17	**17**	66	64	69	68	68	68	**67**
(Am)	High	23	24	26	27	26	24	**25**	81	82	77	75	75	76	**77**
JCD	Low	7	9	16	19	12	7	**15**	34	35	31	42	49	40	**39**
(Bw)	High	23	25	33	37	31	24	**29**	65	57	65	71	68	63	**66**
LA	Low	8	8	9	10	10	8	**9**	53	55	59	58	55	54	**56**
(Cfb)	High	18	19	19	21	22	19	**20**	82	86	87	88	87	82	**85**
Seoul	Low	-9	-7	-2	5	0	-7	**-3**	54	67	62	65	48	52	**57**
(Dwa)	High	-5	-5	-4	3	1	-2	**7**	87	87	91	90	89	88	**89**

JCD = Jacobabad (city in South Pakistan), LA = Loa Angeles.

RESULTS AND DISCUSSION:

The Figure 2 indicates that the required height of vertical sheet for 2 m/sec wind velocity is about 2.5 to 6 cm for the OVRS to be operated in dry, tropical and temperate climate conditions. However, comparatively slightly larger sheet with vertical height is required for operating the OVRS in continental climate conditions. The required vertical sheet height for the selected climate conditions is not so high.

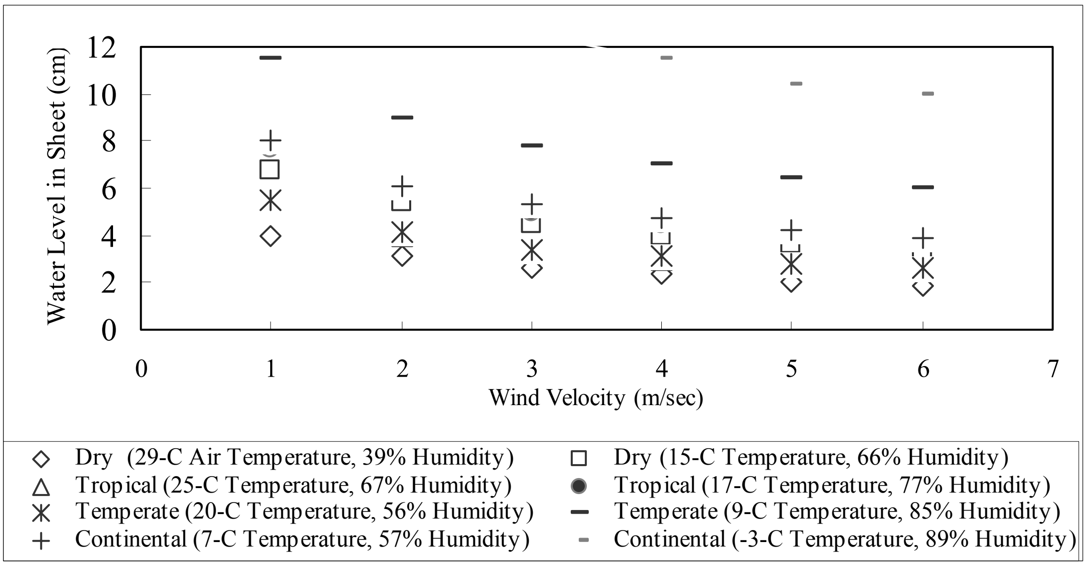

Figure 2: Height of vertical sheet for 80% volume reduction per day for various climate regions.

The Figure 3 indicates that 773 to 1600 cm wide vertical sheet would be required for the dry, tropical and temperate climate conditions when wind velocity is 2 m/sec. This height is not so large for setting up this system at household level. However, the continental climate requires comparatively bigger width of about 1600~6303 cm.

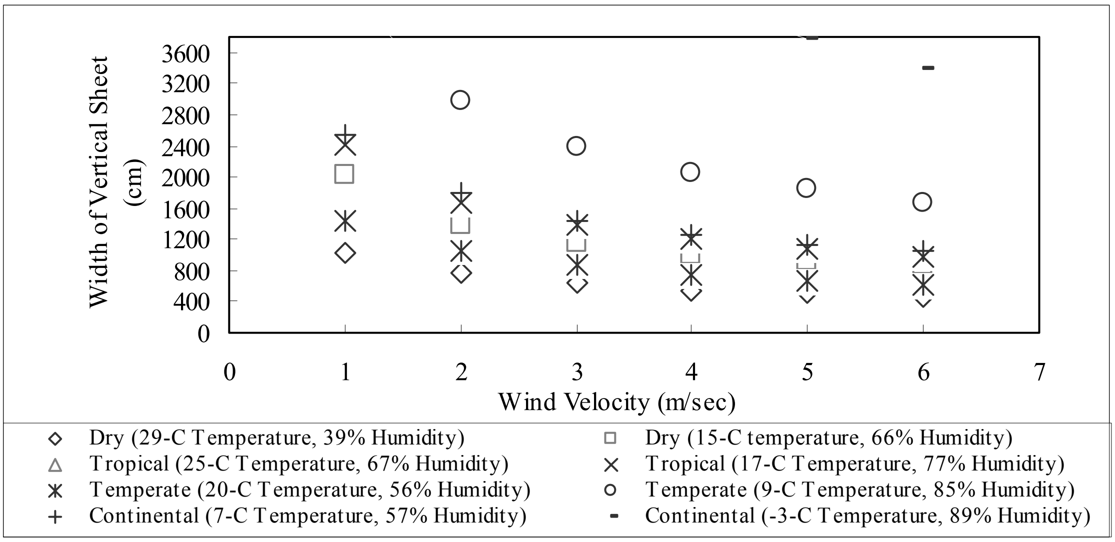

Figure 3: Width of the vertical sheet for 80% volume reduction per day for various climate regions.

This Figure 4 indicates that size of sheet required for dry, tropical and temperate climates is 2396~ 10000 cm^2, which is not so big for setting up system at household level. However, the continental climate requires size of vertical sheet more than 11000 cm^2 which is slightly larger.

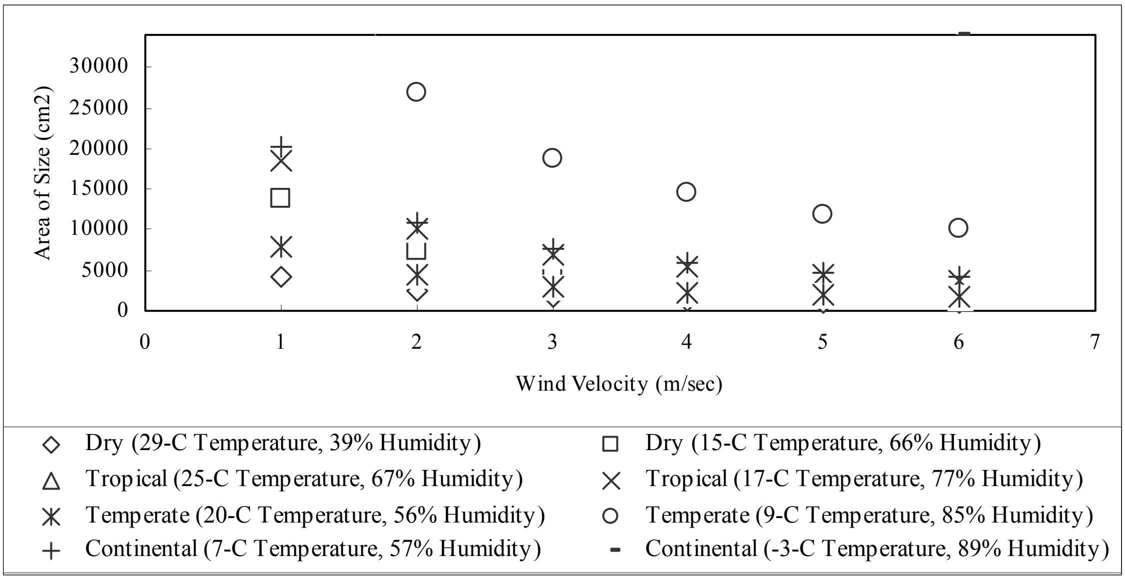

Figure 4: Size of vertical sheet for 80% volume reduction per day for various climate regions.

The dimensions of vertical sheet and wind tunnel proposed for dry, tropical, temperate and continental climate is summarized in the Table 5.

Table 5: Estimated dimensions of vertical sheet (for 12 hours drying during day) and wind tunnel.

Climate Regions with air temperature and air humidity	Dimensions of Vertical Sheet			Dimensions of Evaporation Chamber			Wind Velocity (m/sec)
	Width (cm)	No. of Sheet	Height (cm)	Width (cm)	Length (cm)	Height (cm)	
Dry:29-C, 39% Humidity	773	6	3.1	100	140	12	2
Tropical:25-C,67% Humidity	1044	9	4	120	140	12	2
Temperate:20-C,56% Humidity	1052	9	4.1	120	140	12	2
Continental:7-C,57% Humidity	1785	18	6.1	120	140	14	2

CONCLUSION:

The OVRS is quite feasible for setting up and operating at household level for dry, tropical, temperate and continental climates with the adequately small sizes of vertical sheets to achieve the treatment of desired volume of urine. The concluding observations are stated as under:

- **Dr Climate:** The smallest size of 2396~7487 cm^2 for 12 is required for setting up this system in dry climate.
- **Tropical Climate:** The required size of vertical sheet for OVRS in tropical climate region is 4177 ~ 9999 cm^2 for 12 hours during day or night time operation, which is adequately small for setting up at household level.
- **Temperate Climate:** The size of vertical sheet for setting up the OVRS in temperate climate is 4315 ~ 26806 cm^2 for 12 hour in day or night operation respectively. It is recommended to design and operate the OVRS in temperate climate during day time with a reasonable size of vertical sheet.
- **Continental Climate:** The OVRS can be operated with size of vertical sheet ranging between 10887 ~ 90768 cm^2 in continental climate. It can be recommend to design and operate the OVRS in continental climate during day time with reasonable size of sheet.

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