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1 Dehumidification of sewage sludge using quonset solar tunnel dryer: an 2 experimental and numerical approach Faraz Afshari¹, Ataollah Khanlari², Azim Doğuş Tuncer^{3,4*}, Adnan Sözen⁵, İstemihan 3 Şahinkesen³, Giovanni Di Nicola⁶ 4 567890 10 ¹Mechanical Engineering, Faculty of Engineering, Erzurum Technical University, Erzurum, Turkey ²Mechanical Engineering, Faculty of Engineering, University of Turkish Aeronautical Association, Ankara, Turkey ³Energy Systems Engineering, Faculty of Engineering-Architecture, Burdur Mehmet Akif Ersoy University, Burdur, Turkey ⁴Institute of Natural and Applied Sciences, Gazi University, Ankara, Turkey ⁵Energy Systems Engineering, Faculty of Technology, Gazi University, Ankara, Turkey ⁶Department of Industrial Engineering and Mathematical Sciences (DIISM), Università Politecnica delle Marche, Ancona, Italy 11

12 Abstract

13 In this study, it is aimed to design an efficient and sustainable solar tunnel dryer to be 14 used in drying process of sewage sludge. In the first step of this study, heat and flow structure of three tunnel dryers including rectangular tunnel (RSTD), quonset tunnel 15 (QSTD) and guonset tunnel with fins (QSTD/F) have been numerically surveyed to 16 17 determine the effective design. Based on CFD results, guonset-type tunnel designs 18 have been fabricated, experimentally analyzed and compared with numerical findings. 19 In this work, different from previous studies on quonset-type solar-thermal systems, 20 top surface of Quonset geometry was made from sheet metal as an absorber to 21 enhance heat transfer area. The drying tests have been performed in different months 22 of the year (June and January) by applying two different air velocities to evaluate the 23 performance of tunnel dryers at various climatic conditions. Integrating fins to the 24 quonset tunnel had considerable positive effects on both thermal and drying 25 performances. According to the experimental findings, specific moisture extraction rate 26 (SMER) value was attained on June and January in the range of 0.50e0.89 and 27 0.39e0.65 kg/kWh, respectively. The results indicated the successfulness of guonset 28 solar tunnel dryer design in the dehumidification process of sewage sludge.

- 29
- 30
- 31 Keywords: Quonset, solar tunnel dryer, sewage sludge, solar thermal, solar drying.

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- 34

Nomenclature					
A_{SD}	area (m ²)				
СОР	Coefficient of performance				
Cp	specific heat capacity of air (kJ/kgK)				
D _{hd}	hydraulic diameter (m)				
DR	drying rate (g water/g dry matter min)				
E _{fn}	overall consumed electrical energy (kJ)				
EE	energy efficiency of the drying system (%)				
G _b	generation of turbulence kinetic energy due to buoyancy (m ² /s ²)				
G _k	generation of turbulence kinetic energy due to the mean velocity				
	gradients (m ² /s ²)				
h _{fg}	latent heat (kJ/kg)				
Ι	solar radiation (W/m ²)				
k	thermal conductivity (W/mK)				
'n	mass flow rate (kg/s)				
МС	moisture content (g water/g dry matter)				
M _d	final dry weight (g)				
M _i	initial wet weight (g)				
M _m	removed water (kg)				
Nu	Nusselt number				
QSTD	Quonset solar tunnel dryer				
QSTD/F	Quonset solar tunnel dryer with fins				
Q_r	energy for the moisture removal (kJ)				
\dot{Q}_{uf}	useful heat rate (W)				
Re	Reynolds number				
RSTD	Rectangular solar tunnel dryer				
SEC	specific energy consumption (kWh/kg)				
SMER	specific moisture extraction rate (kg/kWh)				
Т	temperature (K)				
V	air velocity (m/s)				
\vec{v}	overall velocity vector (m/s)				
$\overline{\mathbf{w}_1,\mathbf{w}_2,\mathbf{w}_n}$	the uncertainties in the independent variables				

W _{fn}	fan power (W)				
W_R	Total uncertainty (%)				
X _t	moisture content at time "t" (g water/g dry matter)				
X_{t+dt}	moisture content at time "t+dt" (g water/g dry matter)				
Greek letters					
α	absorptivity				
αε	inverse effective Prandtl numbers for ε				
α_k	inverse effective Prandtl numbers for k				
λ	heat transfer coefficient (W/m ² K)				
μ	dynamic viscosity of air (Pa.s)				
ρ	density of air (kg/m ³)				
τ	transmissivity				
ω	specific humidity (g/g)				
Subscripts					
in	inlet				
out	outlet				
а	air				

36 1. Introduction

37 Supplying continuous and inexpensive energy resources is an important issue for 38 countries that directly affect industrial and economic growth. Decreasing fossil 39 reserves, environmental pollution and considering crude oil prices, renewable energy 40 sources like solar energy has become an important matter of concern over the past 41 decades [1-2]. Different studies were performed with the aim of analyzing 42 environmental problems related to the conventional energy sources and the benefits 43 of using clean energy systems. Also, a number of researches have been numerically 44 and experimentally investigated renewable energy harvesting methods from different 45 aspects of view. Investigating various studies showed that solar energy as a widely 46 accessible clean and sustainable energy source can be used to obtain sustainable 47 energy systems [3]. Utilizing efficient and innovative modifications, increasing the 48 overall performance of renewable energy based systems, and combination with other 49 energy systems are some of the top priority of available researches in the field of solar

50 energy [4]. There is a remarkable attention to design innovative, cost-effective, simple 51 structured and efficient solar-thermal energy systems with capability of absorbing high amount of solar energy [5]. Different types of solar thermal collectors were discussed 52 53 in a study by Kalogirou [6]. Investigations on active solar energy systems indicates that 54 integration of solar energy based systems can reduce the heating and cooling loads 55 [7-9]. In addition, solar energy could be utilized with the aim of decreasing energy 56 consumption in drying procedure which is an energy intensive process. Various types of direct and indirect solar-assisted drying systems are extensively investigated by 57 58 different researchers all over the world [10]. Combining solar collectors with different 59 drying systems could enhance the overall performance of the dryer. In a study 60 performed by Ceylan and Gürel [11], a solar assisted a fluidized bed drying system 61 combined with a heat pump with the aim of improving the efficiency of the system. In 62 another study, Singh et al [12] indirect-expansion solar-infrared combined with a heat 63 pump dryer to be utilized in drying agricultural crops. Also, Veeramanipriya, and 64 Umayal Sundari [13] developed a hybrid photovoltaic thermal solar drying system with 65 the purpose of capturing thermal energy and increasing the overall performance of the 66 system.

67

68 Treatment of municipal sewage sludge is an important issue especially in big cities. In 69 this context, sewage sludge can be dried by different drying methods and utilized in 70 various applications that can decrease negative effects of direct disposal of sludge. 71 Roof solar drying method was investigated by Wang et al. [14] in order to drying 72 sewage sludge by using a sandwich-like chamber bed system. A combined system 73 was designed by Di Fraia et al. [15] to use both solar energy and biogas as two different 74 heat sources to be utilized for sewage sludge drying. In another work, a convex-type 75 absorber was designed and manufactured by Tuncer et al. [16] for drying municipal 76 sewage sludge. In a similar research numerical modeling method was used to analyze 77 heat and moisture transfer of sewage sludge over drying process [17]. In another study, 78 energy demand and drying behavior of a pilot-scale microwave system for sludge 79 drying was investigated. In addition, drying rate, exposure time, and specific energy 80 consumption were calculated to evaluate the performance of the dryer [18].

81 Solar tunnel drying systems have recently received remarkable consideration among 82 community of researcher and engineers. Mewa et al. [19] conducted an experimental 83 work to evaluate beef drying kinetics by using a solar tunnel dryer. Over the test time, 84 different parameters were monitored and considered in calculations such as ambient 85 humidity and temperature, air flow rate and solar radiation. Karthikeyan et al. [20] 86 studied the drying kinetics of curcuma longa in a mixed mode forced convection 87 utilizing solar tunnel drying system. Also, exergy analysis was performed using the 88 obtained data from the experiments to evaluate the developed solar tunnel dryer. In 89 another research, direct and indirect solar dryers were developed and their 90 performance was evaluated in drying sewage sludge [21]. Also, a modified type of 91 parabolic solar tunnel dryer was used with the aim of drying Andrographis paniculata 92 [22]. In addition, solar tunnel applications have been performed in order to drying 93 different agricultural products including potato chips, peppermint plants, ghost chilli 94 pepper and mint [23-26].

95 Computational fluid dynamics (CFD) has been known as a numerical method used for 96 simulating different energy systems which is widely utilized by different researchers. In 97 the open literature, there are many scientific works on different solar energy-based 98 systems like solar air heaters performed by using CFD as valuable method for 99 evaluating the performance of the systems before manufacturing them [27-28]. Raj et 100 al. [29] utilized CFD modeling with the aim of analyzing macro-encapsulated latent heat 101 storage technique in a solar heating system. In other study, an artificially roughened 102 solar air heater was simulated to determine the effect of various baffle modifications 103 on the efficiency [30].

104 Drying sewage sludge is an important issue that has been studied by some 105 researchers. The main purpose of dehumidifying sewage sludge is utilizing them in 106 various applications. In this work, it is attempted to design an efficient and sustainable 107 solar tunnel drying system to be used in drying process of sewage sludge. In this 108 context, three various solar tunnel drying systems including rectangular tunnel (RSTD), 109 quonset tunnel (QSTD) and quonset tunnel with fins (QSTD/F) have been investigated 110 with the aim of improving heat transfer. The major purpose of this work is determining 111 the most suitable configuration for solar tunnel dryer. Also, it was aimed to specify the 112 performance of solar energy-based tunnel dryers in drying process of sewage sludge. 113 In this manner, heat and flow structure of three tunnel dryers have been numerically

- 114 surveyed to select the effective design. In addition, effective tunnel designs have been
- 115 fabricated, experimentally analyzed and compared with simulation results. In Fig. 1,
- 116 main steps of the present research is displayed and explained briefly.



Fig. 1. Main steps of the present study

119

117

2. CFD simulation 120

121 Computational fluid dynamics is an important tool with outstanding accuracy and 122 flexibility used in different investigations, which involves the use of the basic laws of 123 energy, governing equations and modeling a physical problem. CFD simulation is a 124 very useful method to analyze the pressure, velocity, temperature, and density of 125 analyzed zone. This technique is widely used by researchers to compare with 126 experimental work and to closely monitor the flow structure and temperature 127 distribution of the utilized fluid. This methodology, is used especially for the purpose of 128 revealing the structure of flow field, which can be very useful because flow imaging is 129 a very difficult process and sometimes just impossible for some experimental works. 130 In this section, three different tunnel dryers have been analyzed to determine the most 131 suitable geometry of tunnel dryer. In this regard, rectangular tunnel (RSTD), quonset 132 tunnel (QSTD) and quonset tunnel with fins (QSTD/F) have been generated and 133 analyzed. In Fig. 2, geometry and boundary conditions for analyzed solar tunnel dryers 134 are given. Inlet, outlet, solar radiation and fins placement are clearly displayed in Fig.

135 2. Mesh generation is another important step in the numerical analysis. In Fig. 3, the 136 generated mesh configurations of test tunnels have been provided for all geometries. 137 Various mesh types, configurations and modifications have been performed to achieve 138 appropriate mesh structure for each geometry and consequently obtaining high 139 accuracy in the numerical outcomes. As shown in the Fig. 3, triangle mesh and 140 curvature mode were utilized with 1.2 growth rate. The skewness quality factor as a 141 significant parameter was evaluated in mesh generation process. For generated 142 meshes, average and highest skewness values in this case study varied between 0.23-143 0.26 and 0.80-0.84, respectively. Moreover, mesh elements number of the models in 144 RSTD, QSTD and QSTD/F dryers were obtained as 1430000, 1450000 and 1490000, 145 respectively.

146





Fig. 2. Geometry and boundary condition for solar tunnel dryers



152 The main aims of CFD analysis in this study are determining the most suitable 153 geometry for tunnel dryer and specifying the effect of integrating fins. In this regard a 154 steady-state model has been utilized in CFD simulation part. In this research, the effect 155 of air specific humidity is neglected and the thermal performance of the system is 156 analyzed. In other words, the potential of the designed tunnel dryers in heating flowing 157 air is investigated. In this study, dried sample is sewage sludge and unlike agricultural 158 products high air temperature is intended to reduce drying time. In accordance with 159 experimental conditions, boundary values have been defined to apply in the derivation 160 of energy, continuity and momentum equations. Defined problem was assumed to be 161 a three-dimensional geometry under a turbulent flow. Governing equations are given 162 as:

163 Mass conservation:

$$164 \quad \nabla . \left(\rho . \, \vec{v}\right) = 0 \tag{1}$$

165 Momentum balance:

166
$$\nabla . (\rho. \vec{v}. \vec{v}) = -\nabla p + \nabla . (\mu \left[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla . \vec{v}I \right])$$
(2)

167 Energy conservation balance:

168
$$\nabla . \left(\vec{V} (\rho E + p) \right) = \nabla . k_{eff} \nabla T - h \vec{J} + \left(\mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla . \vec{v} I \right] . \vec{v} \right)$$
(3)

169 In the CFD method, $k - \varepsilon$ viscous model is known as one of the most useful models 170 which is appropriate for turbulence flow. Basically, two transport equations are 171 employed in solution of this method, which are known as "*k*" for turbulent kinetic energy 172 and " ε ", for the rate of dissipation of kinetic energy. In this work, $k - \varepsilon$ RNG model has 173 been used in solution which can be expressed by following equations [31]:

174
$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{4}$$

175
$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_i}\left(\alpha_{\varepsilon}\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_{\varepsilon} + S_{\varepsilon}$$
(5)

here, S_k and S_{ε} are source terms. Y_M shows contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation Also, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are model constants.

179 **3. Material and Method**

180 **3.1. System design**

181 In the experimental analysis part of this work, tunnel dryers with two different 182 geometries have been manufactured for sustainable solar assisted dryers by 183 considering CFD simulation results. The obtained results in numerical analysis part 184 and analyzing the presented studies in the literature indicated the superiority of 185 quonset geometry in comparison to rectangular geometry [32-35]. In this regard, two 186 different quonset type solar tunnel dryers have been fabricated to be tested 187 experimentally. The first one was named as quonset type solar tunnel dryer (QSTD). 188 In the second one, 5 fins placed on absorber surface and 4 fins on the dryer floor and 189 was named as guonset type solar tunnel dryer with fins (QSTD/F). Both dryers' bottom 190 side has a base size of 1000x300 mm. The radius of guonset absorber is 150 mm. The 191 fins added to QSTD/F dryer placed 50 mm after the fan inlet and their dimensions are 192 as 50x500 mm. In Fig. 4, the internal details of the dryers are shown.



201 of both dryers. In addition, 20 mm thick extruded polystyrene thermal insulation 202 material was used in the air inlets and outlets. In the experiments, 40 W alternating 203 current fans were used and suitable dimmer switches were added to control air velocity in the system. A schematic diagram and a photograph of the experimental setups areshown in Fig. 5.



- **Fig. 5.** Experimental setup of tunnel dryers; a) Schematic diagram, (b) Photograph

211 **3.3. Experimental procedure**

212 In this study, both QSTD and QSTD/F systems were tested simultaneously to analyze 213 their performance and examine the effect of adding fins to guonset type dryer. The 214 experiments were carried out on June and January on four different days by applying 215 two different air velocities to compare the performance of tunnel dryers at various 216 climatic conditions. This experimental process could provide a general view about the 217 performance of the manufactured tunnel dryers. In the experiments, air velocities were 218 set to 3 m/s (Exp. 1) and 2 m/s (Exp. 2). These air velocities correspond to 0.014 kg/s 219 and 0.009 kg/s air mass flow, respectively. Air flow rate is an important factor in drying 220 applications. It should be indicated that air flow above the drying sample has two 221 different duties containing cooling effect and conveying evaporated moisture from 222 drying sample surface. It is clear that high air flow rate leads to increases in cooling 223 impact, so the evaporation rate reduces. Consequently, the optimum flow rate is 224 needed to achieve a balance among sample cooling and removal of evaporated 225 moisture. In this work, the experiments have been conducted at two different air flow 226 rates including 0.014 kg/s and 0.009 kg/s regarding to similar drying application in the 227 literature [11,36, 37]. Before starting the experiments, both systems were kept covered 228 in ambient conditions and turned to the south. Moreover, the fans were started to run 229 20 minutes before starting experiments.

230 Sewage sludge samples with the density of 1370 kg/m³ were placed in both systems 231 as 100 grams in per tray. The tray is located 80 mm above from the baseplate and the 232 tray dimensions are 250x250 mm. The tray is positioned 100 mm away from the air 233 outlet. The purpose of this placement is to make maximum use of the heated air. 234 Temperature measurements were performed by K-type thermocouples. Temperature 235 values were measured every 5 seconds and recorded with the help of data loggers. 236 Air velocity, solar radiation and mass flow variations were measured at 20 minutes 237 intervals by using anemometer, solar meter and digital balance, respectively. Details 238 of measuring equipment can be seen in Fig. 5. Used sewage sludge drying sample 239 had a premier moisture content of 4.50±0.30 g water/g dry matter. The performance 240 tests begun at 09:00 AM and ended when the difference among two weight measuring 241 was lower than 1%.

242

243 **4. Theoretical calculations**

In this part, the used expressions in investigating quonset type solar tunnel dryers are
given. Mass conversation of air and moisture could be expressed by using Eq. (6) and
Eq. (7), respectively:

$$247 \qquad \sum \dot{m}_{in,a} = \sum \dot{m}_{out,a} \tag{6}$$

248
$$\sum (\dot{m}_{in,a}.\omega_{in,a} + \dot{m}_m) = \sum \dot{m}_{out,a}.\omega_{out,a}$$
 (7)

249 The energy balance in the quoset type dryer could be defined as:

250
$$\dot{Q}_{in} - \dot{Q}_{loss} = \dot{m}_a (h_{out,a} - h_{in,a})$$
 (8)

251 The input thermal energy to the solar dryer can be obtained by using Eq. (9):

$$252 \quad \dot{Q}_{in} = \alpha.\tau.I.A_{SD} \tag{9}$$

253 The gained useful thermal energy in the solar drying system could be found as:

254
$$\dot{Q}_{uf} = \dot{m}_a \cdot c_p \cdot \left(T_{out,a} - T_{in,a} \right)$$
 (10)

255 Coefficient of performance (COP) is a substantial metric in investigating energy 256 applications. COP can be defined as the ratio of overall gained thermal energy to total 257 used electrical power. In this study, the overall used electrical power refers to utilized 258 fan power. COP could be calculated by utilizing Eq. (11):

$$259 \quad COP = \frac{V_{a} \cdot \rho \cdot c_p \cdot (T_{out,a} - T_{in,a})}{W_{fn}} \tag{11}$$

260 Reynolds and Nusselt numbers are important dimensionless metrics that are utilized 261 in investigating thermal and flow behavior. Reynolds number could be achieved by 262 using Eq. (12) [38]:

$$263 \qquad Re = \frac{\rho \cdot V \cdot D_{hd}}{\mu} \tag{12}$$

264 Nusselt number can be found as:

$$265 \qquad Nu = \frac{\lambda D_{hd}}{k} \tag{13}$$

266 Specific moisture extraction rate (SMER) and specific energy consumption (SEC) are

crucial parameters that could be used for analyzing the effectiveness of dryers. SMER
can be defined as the amount of moisture extracted per used electrical energy and can
be calculated as:

$$270 \quad SMER = M_m/E_{fn} \tag{14}$$

Energy efficiency of the dryer (EE) is a crucial metric to investigate the effectiveness of the developed and analyzed drying system. It could be achieved by dividing the amount of needed thermal energy to extract moisture from the sample to required electrical energy. EE could be obtained as:

$$275 \quad EE = Q_r / E_{fn} \tag{15}$$

The thermal energy used to extract moisture from municipal sewage sludge sample could be obtained by using Eq. (16) [16]:

$$278 \qquad Q_r = h_{fg} \cdot M_m \tag{16}$$

279 Moisture content on dry basis and drying rate can be found with the help of the 280 following expressions [39]:

$$281 \qquad MC = \left(\frac{M_i - M_d}{M_d}\right) 100 \tag{17}$$

$$282 DR = \frac{X_{t+dt} - X_t}{dt} (18)$$

283 General expression for experimental uncertainty can be expressed as [40-41]:

284
$$W_{R} = \left[\left(\frac{\partial R}{\partial x_{1}} w_{1} \right)^{2} + \left(\frac{\partial R}{\partial x_{2}} w_{2} \right)^{2} + \dots + \left(\frac{\partial R}{\partial x_{n}} w_{n} \right)^{2} \right]^{1/2}$$
(19)
285
286
287
288
289

291 **5. Results and Discussion**

292 **5.1. CFD Results**

293 In this section, the obtained numerical results for different designs and operating 294 conditions are given and explained. CFD analysis have been done considering 295 average conditions of June and January. In this part, temperature and velocity contours 296 related to June condition are presented. Also, in the experimental results section, 297 numerically obtained outlet temperatures related to June and January are presented 298 and compared with experimentally attained outlet temperatures. In Fig. 6, velocity 299 contours of various solar tunnel dryers are presented for two different air velocities. 300 Considering obtained contours, the highest air velocity is seen in the center of the 301 tunnel, and as expected the velocity decreases as it approaches the walls, where 302 velocity value is low as a result of friction. Analyzing velocity distribution in different 303 tunnel dryers indicated that using guonset type tunnel can led to obtain more 304 homogeneous flow inside the dryer. In other words, in rectangular tunnel air flows over 305 the middle part of the tunnel and quit the system. However, in quonset type tunnel 306 more homogenous velocity distribution is available and air flows over all surface that 307 can attain more thermal energy.

In Fig. 7, temperature contours for analyzed solar tunnel dryers have been presented. The effect of air velocity is clearly observed in the obtained temperature contours for different tunnel dryers. The effect of increasing velocity from 2 m/s to 3 m/s on air temperature on reducing the temperature obviously can be seen especially in the boundaries and near walls. In addition, positive impact of using fins in designed QSTD/F system indicates that this type of fins' use can be considered in solar systems to improve thermal characteristics of the solar tunnel dryers.

315 The results obtained from volume rendering method are considered to be one of the 316 most important figures achieved from modeling. The three-dimensional figures 317 obtained by this methodology provide a better perspective for understanding the 318 velocity distribution, flow structure and temperature distribution of the fluid. As it can 319 be clearly shown in Fig. 8a, the temperature level is higher in the areas close to the 320 fins and the heat is transferred from the wall and the fins to the fluid. In addition, velocity 321 volume rendering is given in Fig. 8b. As shown in this figure, the highest velocity values 322 are clearly obtained from the simulation in the entrance (inlet) and exit areas.



QSTD/F, 3 m/s



QSTD/F, 3 m/s



- Fig. 8. Volume rendering images of QSTD/F at 2 m/s air velocity; a) temperature, b)
 velocity

332 5.2. Experimental results

333 The experiments have been carried out at two different air velocities as 2 and 3 m/s. 334 In Fig. 9, time-dependent solar radiation and change of ambient temperature in the 335 experiments done on June and January are given. Since the experiments have been 336 performed on consecutive days on June and January, the values are very close to 337 each other. This issue allows to make reasonable comparisons between obtained 338 results. In the experiments 1, 2, 3 and 4 the average solar radiation values were 339 measured as 836, 858, 734 and 726 W/m², respectively. Also, average ambient 340 temperature values were observed as 25.6°C, 26.2°C, 14.16°C and 13.87°C 341 respectively. Maximum solar radiation values for Exp. 1, Exp. 2, Exp. 3 and Exp. 4 is 342 948, 953, 816 and 828 W/m², respectively.

343 The COP is generally used in thermal systems and is an important parameter for 344 determining the system performance in solar-assisted energy systems. Briefly, the 345 COP value can be defined as the ratio of the useful energy obtained to the consumed 346 energy in the system. The electrical power value as consumed energy for the present 347 system is very low. COP variation with the time is illustrated in Fig. 10. For the 348 experiment 1, COP values were calculated as 4.88 and 4.25 for QSTD/F and QSTD in 349 the experiment performed at 3 m/s air velocity. These values were calculated for the 350 experiment 2 as 4.28 and 3.86 respectively. In the experiment 3, COP for QSTD/F and 351 QSTD was achieved as 4.08 and 3.66, respectively. In addition, in the experiment 4, 352 COP for QSTD/F and QSTD was attained as 3.45 and 3.11, respectively. In a work 353 conducted by Güler et al. [36], a solar dryer was made utilizing a double-flow collector 354 modified with iron mesh. In that study, the obtained COP values were attained in the 355 range of 4.83-5.53. It can be state that, similar results were obtained when compared 356 to the present study. The reason for the relatively higher COP values in the related 357 study arose from harvesting more useful energy by using double-pass structure. In 358 other study performed by Sözen et al. [42], COP value was achieved in the range of 359 3.10-3.87. Also, in another work different turbulator modifications were applied to a 360 tubular solar collector [43] and average COP value was achieved as 3.80. By 361 examining similar academic researches in the literature, it is revealed that, the COP 362 values obtained in this research are in the agreement with other studies.

363



365 Fig. 9. Time dependent variation of solar radiation and ambient temperature values



371 The MC variation with respect to the test time is shown in Fig. 11. From the figure, it 372 can be seen that, in the experiment performed at high air velocity on June, the modified 373 quonset dryer could shorten the drying time by 40 minutes, and by 80 minutes at low 374 air velocity. Also, in the experiments conducted on the winter condition (January) drying 375 time was shortened as 60 and 60 minutes at high and low air velocities, respectively. 376 Accordingly, it can be stated that, both the impacts of air velocity and the fin integration 377 on drying performance of the system are quite significant. The shortest drying time was 378 observed as 220 minutes in the experiment using the fin assisted quonset dryer on 379 June. The influence of air velocity in solar assisted drying systems has been reported 380 in similar available in the literature [44-47].

381 In Fig. 12, SMER change with time is shown. Average SMER values were calculated 382 as 0.89 and 0.76 kg/kWh for QSTD/F and QSTD, respectively in the experiment 383 performed at 3 m/s air velocity on June. For the experiments at the air velocity of 2 m/s 384 on June, it was calculated as 0.55 kg/kWh and 0.50 kg/kWh, respectively. Also, 385 average SMER values in the experiment performed at 3 m/s air velocity on January 386 obtained as 0.65 and 0.54 kg/kWh for QSTD/F and QSTD, respectively. Moreover, 387 average SMER values in the experiment conducted at 2 m/s air velocity on January obtained as 0.43 and 0.39 kg/kWh for QSTD/F and QSTD, respectively. As it was 388 389 expected, the SMER values for both dryers at high air velocity are high. However, 390 longitudinal fins added to QSTD/F caused a significant increase in SMER values.

391 Fig. 13 illustrates a comparison of the SMER values for solar-assisted drying systems 392 in this work and related studies in the literature. As shown in the figure, in some 393 presented studies more complex systems such as solar-assisted fluidized-bed [48]. 394 solar-assisted heat pump [49], photovoltaic-thermal [50] used in drying systems to 395 achieve higher performance. At the same time, it was found that obtained results from 396 present work is in harmony in terms of SMER values compared to similar solar assisted 397 systems performed recently [1, 16, 42, 51-58].

- 398
- 399









- 408

409 Fig. 13. Comparison of obtained SMER values with available studies about solar 410 dryers in the literature

411 Fig. 14 gives the change of DR values with test time. Accordingly, for QSTD/F dryer 412 average DR values were calculated as 0.0018, 0.0011, 0.0010 and 0.0006 g water/g 413 dry matter min for experiment 1, 2, 3 and 4, respectively. DR values were found as 414 0.0013, 0.0007, 0.0006 and 0.0005 g water/g dry matter min for QSTD, for experiment 415 1, 2, 3 and 4, respectively. As seen in Fig. 14, reducing moisture content of sewage 416 sludge sample over the time led to reduce in DR values. It can be expressed that the 417 air mass flow rate has a significant influence on transferring water from sample surface 418 and as a result drying process can be accelerated. It is better to state that agricultural 419 products generally have certain moisture contents. In other words, moisture content of 420 the same product does not significantly vary regionally. This fact makes it possible to 421 determine initial moisture content and adjusting the drying system's set values. In this 422 study, municipal sewage sludge has been dried as sample. Different parameters could 423 affect the characteristics of sewage sludge sample. Therefore, sewage sludge samples 424 provided from different treatment plants have not the same properties. Consequently,

425 adjusting a drying system based on specification of a sewage sludge sample is not 426 reasonable.

427 In the experiments done on June, average energy efficiency (EE) values of QSTD/F 428 and QSTD dryers at 3 m/s air velocity were found as 44.32% and 37.53%, respectively. 429 Also, for low air velocity (2 m/s), average EE values for QSTD/F and QSTD dryers are 430 40.93% and 36.23%, respectively. In the experiments performed on January, average 431 EE values of QSTD/F and QSTD dryers at 3 m/s air velocity were attained as 32.42% 432 and 27.02%, respectively. In addition, average EE values of QSTD/F and QSTD dryers 433 at 2 m/s air velocity were achieved as 25.19% and 22.16%, respectively. As seen, EE 434 values on January experiments are lower than that of the experiments done on June. 435 It can be stated that some factors such as low solar radiation and low ambient 436 temperature affected the performance of drying system negatively in winter. In a study 437 on a solar-assisted waste sludge drying system, EE found in the range of 21-47% [16]. 438 In a study where a solar-assisted system was used for drying agricultural products, 439 these values were calculated in the range of 17-34% [59]. In these two mentioned 440 studies, both air velocity and modifications increased EE values similar to the current 441 research. Since waste sludge was selected as the product to be dried in this study, 442 there is no concern about the product quality, which is important in agricultural 443 products. For this reason, high air velocities can be preferred for efficient drying and 444 high energy efficiency in solar assisted drying systems designed for drying waste 445 sludge.

446





450 Fig. 15 shows the numerical and experimental results of the outlet temperature values. 451 From the figure, it can be seen that the outlet temperature of the rectangular dryer is 452 very low compared to the other systems. For this reason, this model was not used in 453 the experimental study and guonset form dryers were preferred. Experimental and 454 numerical results for low air velocity on June conditions have deviations of 5.14% and 455 5.71% for QSTD/F and QSTD, respectively. Also, these values on June conditions are 456 6.5% and 7.42% respectively for high air velocity. Experimental and numerical findings 457 for low air velocity on January conditions have deviations of 5.24% and 7.43% for 458 QSTD/F and QSTD, respectively. In addition, these values on January conditions are 459 7.74% and 6.92% respectively for high air velocity. Fig. 16 shows a thermal camera 460 image taken during the experiment 1. As it can be seen in Fig. 16, adding fins to the 461 tunnel dryer led to obtain higher temperature in the absorber surface in comparison 462 with unmodified one.

- Table 1 represents the obtained experimental uncertainty values in the performance
 tests. The attained values for experimental uncertainties are in acceptable range when
 compared with literature studies [4, 11, 53].
- 466

467







Fig. 15. Obtained numerical and experimental outlet temperature values



- 470
- 471 Fig. 16. Thermal camera view of the tested solar dryers

472	Table 1.	The obtained	experimental	uncertainty	values

Unit	Uncertainty
С°	±0.64
W/m ²	±16.68
m/s	±0.34
-	±0.24
	Unit °C W/m ² m/s

474 Tunnel dryers are widely utilized in different drying applications. In addition, solar 475 energy assisted tunnel dryers are extensively analyzed by some researchers. Large 476 scale tunnel dryers were developed and analyzed for different scenarios [60-62]. 477 Analyzing available solar tunnel dryers exhibited high potential of this type dryers that 478 could be utilized for drying various products. In some tunnel dryers, transparent cover 479 has been utilized that can be affect the structure and durability of drying system 480 negatively. In this study, pilot scale tunnel dryers have been investigated to 481 demonstrate the effect of integrating fins. Comparing the results of this work and 482 related studies on large scale tunnel dryers indicates that fin modification can be 483 utilized in large scale dryers to improve the thermal performance. Moreover, in a study 484 done by Panli et al. [63] a large-scale roof drying similar to tunnel dryer has been used 485 for drying sewage sludge.

488 6. Conclusion

In the current study, a new tunnel type solar tunnel drying system to be utilized in dehumidification of sewage sludge has been investigated experimentally and numerically. Accordingly, three various tunnel dryers have been developed and numerically analyzed. Then, quonset solar tunnel dryer design has been selected and manufactured regarding to the CFD simulation results. The performance tests were done on June and January to specify the overall performance of tunnel dryers. The main outcomes of the present research could be given as:

- 496 Utilizing fin modification in quonset type dryer has considerable positive effect
 497 on the thermal performance of the system.
- Adding fins to the drying system reduced the drying time notably.
- 499 Specific moisture extraction rate (SMER) value was achieved between the
 500 range of 0.39-0.89 kg/kWh.
- In summer experiments, average COP values for QSTD/F and QSTD were attained between the ranges of 4.28-4.88 and 3.86-4.25, respectively. In winter tests, these values for QSTD/F and QSTD were achieved between the ranges of 3.45-4.08 and 3.11-3.66, respectively.
- EE of the tunnel dryer was averagely increased as 17.2% by utilizing fin
 modification.

507 Consequently, quonset form solar absorber can be successfully utilized in various 508 drying applications. Moreover, in future studies, different fin modifications and thermal 509 energy storage units can be integrated to this successful quonset solar tunnel dryer 510 design to enhance the thermal performance.

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