

Research Paper: AP—Animal Production Technology

Comparing fogging strategies for pig rearing using simulations to determine apparent heat-stress indices

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ARTICLE INFO

Article history: Received 5 December 2006 Accepted 7 October 2007 Available online 26 November 2007 Strategies to reduce the apparent heat-stress indices inside a growing pig building were compared. Two fogging strategies were studied, fogging with the necessary water evaporating to give the same: (i) duration of heat-stress, ' $F_{Duration}$ ', and (ii) intensity of heat-stress, ' $F_{Intensity}$ ', as when using evaporative pads, ' E_{Pads} '. For the whole 5-month period (May–September) under Greek summer conditions strategy ' $F_{Intensity}$ ' was significantly better than strategy ' $F_{Duration}$ ' in terms of heat-stress duration (P < 0.05; reduction 45.1%) and heat-stress intensity (P < 0.01; reduction 70.7%). Also, during the hottest day (Julian 176) it resulted in: (i) a lower daily average inside temperature (28.5 vs. 31.8 °C; reduction 10.4%), (ii) a smaller daily inside dry-bulb temperature variation (8.7 vs. 10.3 °C; reduction 15.5%) and (iii) a higher reduction of peak outside temperature (36.8 °C at 14:00 h), namely 2.9 vs. 0.2 °C, respectively. For both strategies and heat-stress indices July was the most stressful month and May the mildest. In areas characterised by high outside temperatures and scarce water resources strategy ' $F_{Intensity}$ ' should be implemented with caution as larger water quantities, in comparison to strategy ' $F_{Duration}$ ', need to evaporate.

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1. Introduction

It is well documented (Curtis, 1985) that, compared to other species of farm animals, pigs are relatively sensitive to high environmental temperatures. The major reason for their limited capacity to cope with high environmental temperatures is their inability to sweat (Mount, 1979). Several studies (Bond *et al.*, 1959; Nichols *et al.*, 1982; Nienaber *et al.*, 1987; Lopez *et al.*, 1991; Huynh *et al.*, 2005) have shown that elevated environmental temperatures are among the most important parameters, but other factors such as the extent of skin wetness, the stocking density and the air speed at pig level can cause minor or severe heat-stress problems and consequently hinder pig growth and impede their welfare. Evaporative cooling of ventilating air has long been recommended (MWPS-34, 1990) as an effective means to increase the comfort of housed pigs during hot weather conditions. Two common methods for evaporative cooling are evaporative pads and fogging (i.e. the use of fine mist to cool the inside air temperature). According to various studies (Timmons & Baughman, 1983; Bottcher *et al.*, 1991; Panagakis & Axaopoulos, 2006) evaporative pads are more efficient than fogging. However, evaporative pads require significant capital investment (Bridges *et al.*, 1998), and may be the limiting factor in terms of installation. It is therefore important to answer the following question: which fogging strategy must be used so as to obtain results that are comparable to those achieved by evaporative pads?

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Nomenclature		U _{ef}	effective pit heat transfer coefficient, $W m^{-2} \circ C^{-1}$	
l	A	surface area m^2	O_{fl}	W m ^{-2} °C ^{-1}
l	A	pen floor area m^2	ILe	nit floor heat transfer coefficient $Wm^{-2} \circ C^{-1}$
l	Ac	per noor area, m		pit wall heat transfer coefficient $Wm^{-2} \circ C^{-1}$
l	A A	pit hoof area, m ²	U_{pw} V.	yolume of the inside air space m^3
l	r pw	pit waits area, in specific heat of air $k k a^{-1} \circ C^{-1}$	V ₁ 17.	specific volume of the inside air $m^3 kg^{-1}$
l	с _р Ц	nit denth m	υ ₁ \λ/.	inside air humidity ratio kg [H O] kg [dry air] ⁻¹
l	h.	bit deput, in latent heat of water evaporation Ikg^{-1}	1	outside air humidity ratio, kg [1120] kg [dry air] ⁻¹
l	h h	external surface heat transfer coefficient	νν _ο ιίζ.	nig water vaneur production kgc ⁻¹
l	n ₀	$Wm^{-2} \circ C^{-1}$	1 XX	water added due to forging lags ⁻¹
l	т	host stross intensity °Ch	vv m	water added due to logging, kgs
l	I I	total solar irradiance on each envelope compo	Croch L	ottora
l	1 7,1	nent surface Wm^{-2}	Greek	
l	m	nig weight kg	a	surface solar irradiation absorbance
l	m.	ventilation air mass flow rate kgs ⁻¹	ß	fraction of water evaporating in the room
l	Ó.	heat flow through the walls, the door and the roof	p	0 if forging is off or 1 if forging is on
l	Чb		۲ ۸T	difference between the predicted inside dry bulb
l	Ó,	w heat flow through the pen floor W	$\Delta 1$	temperature and the UCT °C
l	Q,	nig latent heat production W	Λ+	time during which animals are housed under
l	Ó.	cooling due to water forging W	Δι	temperatures higher than the UCT h
l	Q _m Ó	nig sensible heat production W	2	soil thermal conductivity $Wm^{-1} \circ C^{-1}$
l	Qs Ó	heat losses due to ventilation. W	N N	multiple of maintenance
l	Q_v	temperature control ventilation rate $m^3 e^{-1}$	v O:	density of inside air kam^{-3}
l		relative humidity control ventilation rate, $m^3 s^{-1}$	$\sum^{p_1} (M)$	C) lumped effective building conscitance $kI^{\circ}C^{-1}$
l	R R	nit wall thermal resistance $m^2 \circ CW^{-1}$	$\Delta \sqrt{101a}$	total heat production for growing pigs housed at
l	T.	inside air temperature °C	Ψtot	20°C W
l	T T	outside air temperature °C	Φ^*	total heat production for a single growing nig at
l	T.	col air tomporature °C	₽tot	temperatures other than 20°C W
l	1 sa,1 +	time c	Φ_{1}^{*}	latent heat production at house level W
	т. Т.	overall heat transfer coefficient of each surface	Φ^*	sensible heat production at house level. W
	O_{bl}	Wm^{-2} °C ⁻¹	* sen	sensible near production at nouse rever, w
		····· ··· ··· ··· ··· ··· ··· ··· ···		

Following the work presented in Panagakis and Axaopoulos (2006), which compared fogging and evaporative pads, the objective of this study was to compare, via simulation, two fogging strategies, which had the same water evaporating per pig and produced the same: (i) duration of heat-stress, 'F_{Duration}', and (ii) intensity of heat-stress, 'F_{Intensity}', as evaporative pads; 'E_{Pads}'.

2. Materials and methods

2.1. Energy inputs

2.1.1. Fogging

Both the evaporative pads and the fogging were operated when the inside dry-bulb temperature exceeded the upper critical temperature (UCT), which was calculated to be 26.1 °C (Bruce, 1981), and the interior relative humidity was not above 80% (Bridges *et al.*, 1992).

The following time-dependent equations were used to calculate the dry-bulb temperature and relative humidity inside the pig building:

$$\sum (M_a C_a) \frac{dT_i}{dt} = \dot{Q}_s + \dot{Q}_b + \dot{Q}_f + \dot{Q}_v - \gamma \dot{Q}_m, \tag{1}$$

where $\sum (M_a C_a)$ is the lumped effective building capacitance in kJ °C⁻¹, T_i is the inside dry-bulb air temperature in °C, t is the time in s, \dot{Q}_s is the pig sensible heat production in W, \dot{Q}_b is the heat flow through the walls, the door and the roof in W, \dot{Q}_f is the heat flow through the pen floor in W, \dot{Q}_v is the heat losses due to ventilation in W, γ is either 0 (fogging is off) or 1 (fogging is on) and \dot{Q}_m is cooling due to water fogging in W

$$\rho_i \mathbf{V}_i \frac{\mathrm{d}\mathbf{W}_i}{\mathrm{d}t} = \dot{m}_a (\mathbf{W}_o - \mathbf{W}_i) + \dot{\mathbf{W}}_1 + \gamma \dot{\mathbf{W}}_m, \tag{2}$$

where ρ_i is the density of inside air in kgm⁻³, V_i is the volume of the inside air space in m³, \dot{m}_a is the ventilation air mass flow rate in kgs⁻¹, W_o is the outside air humidity ratio in kg [H₂O] kg [dry air]⁻¹, W_i is the inside air humidity ratio in kg [H₂O] kg [dry air]⁻¹, \dot{W}_i is the pig water vapour production in kgs⁻¹ and \dot{W}_m is water added due to fogging in kgs⁻¹.

Analytical equations for the aforementioned flows are presented in the following sections. Hourly weather data from the Athenian region were used and included: dry-bulb temperature, relative humidity, solar irradiance on a horizontal surface and wind speed. Structural and animal data are given in Table 1.

Table 1 – Structural and animal data used in the simulation

Building location	
Athens	Lat 37°58′N, long 23°43′E
Type of huilding	Environmentally controlled
Building dimensions m	Environmentally controlled
Width	9 70
Length	24.20
Height	2 50-4 76
meight	2.30-4.76
R-values, $m^2 \circ C W^{-1}$	
Walls	1.43
Door	1.15
Roof	2.46
Pit walls	1.11
Pit floor	1.16
Type of ventilation	Mechanical
Floor type	Concrete slats
Animal weight, kg	50
Number of animals	300
Animals per pen	15
Feed level	$3 \times level of maintenance$

2.1.2. Pig sensible and latent heat production

Pigs are homoeothermic and strive to maintain their body temperature at 39 °C through the control of total heat dissipation exchange with their environment (Mount, 1968). Total heat dissipation is the sum of sensible and latent heat production. The values of both sensible and latent heat production are calculated using individual animal heat production (measured experimentally in environmental chambers at 20 °C) and the influence of various housing factors such as relative humidity, flooring system, stocking density, feeding and watering systems, etc. (Sällvik & Pedersen, 1999).

Based on the analysis of Blanes and Pedersen (2005) the total heat losses Φ_{tot} for growing pigs at 20 °C are given by

$$\Phi_{\text{tot}} = 5.09m^{0.75} + [1 - (0.47 + 0.003m)](v \, 5.09m^{0.75} - 5.09m^{0.75}), \tag{3}$$

where *m* is the pig weight in kg and v is the multiple of maintenance.

The total heat production Φ_{tot}^* at temperatures other than 20 °C is given by Eq. (4), whereas the sensible heat production at house level Φ_{sen}^* is given from Eq. (5). This last is multiplied with the number of animals housed in the building and used as \dot{Q}_s , namely the pigs' sensible heat production used in Eq. (1):

$$\Phi_{\rm tot}^* = \Phi_{\rm tot} + 0.012 \Phi_{\rm tot} (20 - T_{\rm i}), \tag{4}$$

$$\Phi_{sen}^* = 0.62\Phi_{tot}^* - 1.15 \times 10^{-7} T_i^6.$$
(5)

The pig latent heat production at house level, Φ_{lat}^* , is calculated using

$$\Phi_{lat}^* = \Phi_{tot}^* - \Phi_{sen}^*. \tag{6}$$

This value is then multiplied by the number of animals housed in the building, resulting in \dot{Q}_i , namely the pigs' latent

heat production (W), and finally converted to pig water vapour production (\dot{W}_l) using the latent heat of water evaporation (h_{fg} , J kg⁻¹), which is calculated from the expression: (2501–2.42T_i) × 10³.

2.1.3. Structural heat losses

The heat flow through the building envelope (\dot{Q}_b) is the sum of the heat fluxes entering or leaving each vertical wall, the roof and the door. It can be expressed, using the concept of sol-air temperature which according to Albright (1990) is an equivalent air temperature which would cause heat to be exchanged by the same magnitude as that exchanged when actual temperature, thermal radiation and solar heating are considered as follows:

$$\dot{Q}_b = \sum_i U_{bi} A_{bi} (T_i - T_{sa,i}),$$
 (7)

where U_{bi} is the overall heat transfer coefficient of each building envelope surface in $W m^{-2} \circ C^{-1}$, A_{bi} is the area of each building envelope surface in m^2 and $T_{sa,i}$ is the sol-air temperature in °C.

The overall heat transfer coefficient (U_{bi}) can be calculated by applying the series thermal resistance theory, taking into account the composite layers making up the envelope components. The sol-air temperature is calculated for each structural element using the following equation (ASHRAE, 1989):

$$T_{sa,i} = T_o + \frac{\alpha I_{T,i}}{h_o},$$
(8)

where T_o is the outside temperature in °C, α is the surface solar irradiation absorbance, $I_{T,i}$ is the total solar irradiance on each envelope component surface in W m⁻² and h_o is the external surface heat transfer coefficient in W m⁻² °C⁻¹.

At any time step, the program calculates the total solar irradiance incident upon the surface of the four differently orientated walls (i.e. south, east, north and west) and the roof. Its value depends on the orientation of each surface and the time of the year.

2.1.4. Pen floor heat losses

The heat flow through the pen floor to the soil can be written in terms of the effective heat transfer coefficient (U_{ef}) defined by combining the heat transfer coefficients for pen floors (U_{fl}) pit walls (U_{pw}) , and pit floor (U_{pf}) along the corresponding heat flow path to the outside air. More specifically, the heat flow is computed from the following equation:

$$\dot{Q}_f = U_{ef} A_{fl} (T_i - T_o), \tag{9}$$

where U_{ef} is the effective pit heat transfer coefficient in $W\,m^{-2}\,^\circ C^{-1}$ and A_{fl} is the pen floor area in $m^2.$

The effective heat transfer coefficient is calculated as

$$U_{ef} = U_{fl} + \frac{A_{pw}U_{pw} + A_{pf}U_{pf}}{A_{fl}},$$
 (10)

where U_{fl} is the overall heat transfer coefficient of pen floor in $W m^{-2} \circ C^{-1}$, A_{pw} is the pit wall area in m^2 , U_{pw} is the pit wall heat transfer coefficient in $W m^{-2} \circ C^{-1}$, A_{pf} is the pit floor area in m^2 and U_{pf} is the pit floor heat transfer coefficient in $W m^{-2} \circ C^{-1}$.

The pit of the pig building was considered as a below-grade wall structure. The pit wall heat transfer coefficient is determined from Eq. (10) (CIRA, 1982), which is used for the estimation of below-grade wall heat losses. This equation is in adequate agreement with the results of detailed two-dimensional transient computer modelling (Shipp & Broderick, 1981):

$$U_{pw} = \frac{2\lambda}{\pi H} \ln\left(1 + \frac{\pi H}{2\lambda R}\right),\tag{11}$$

where λ is the soil thermal conductivity in W m⁻¹ °C⁻¹, H is the pit depth in m and R is the pit wall thermal resistance in m² °C W⁻¹.

The pit floor heat transfer coefficient is calculated by applying the series thermal resistance theory for the pit floor, the manure and the pit air. The pen floor heat transfer coefficient is calculated using the slab thermal resistance between the pig building air and the pit air.

2.1.5. Fogging cooling

The fogging cooling term is calculated using the following equation:

$$\dot{\mathbf{Q}}_m = \beta \dot{\mathbf{W}}_m h_{fg},\tag{12}$$

where β is the fraction of water evaporating in the room. In our analysis β was considered equal to 1.0 and constant under the assumptions (Bottcher & Baughman, 1990) that: (1) the very fine fog evaporated completely, (2) the interior psychometric conditions did not vary considerably or approach saturation and (3) the interior air velocities and fogging pressure remained relatively constant. It should be noted that if β is less than 1.0 then the amount of water used would increase accordingly.

2.1.6. Ventilation heat losses

At each time step, the values of the ventilation rate are determined using one of the following equations for temperature and relative humidity, respectively. The higher value of the ventilation rate is selected (Albright, 1990) and the corresponding ventilation heat loss term (\dot{Q}_V) is

substituted into Eq. (1):

$$Q_{V(T_i)} = \frac{\nu_i (\dot{Q}_s - \dot{Q}_b - \dot{Q}_f)}{1000 c_p (T_i - T_o)},$$
(13)

where $Q_{\nu(T_i)}$ is the temperature control ventilation rate in $m^3 s^{-1}$, v_i is the specific volume of the inside air in $m^3 kg^{-1}$ and c_p is the specific heat of air in $kJkg^{-1} \circ C^{-1}$.

$$Q_{V(RH_i)} = \frac{v_i(W_1 + W_m)}{3600(W_i - W_o)},$$
(14)

where $Q_{\nu(\text{RH}_i)}$ is the relative humidity control ventilation rate in $m^3 s^{-1}.$

2.2. Heat-stress indices

Two heat-stress indices were used in the analysis, namely: the duration of heat-stress and the intensity of heat-stress (Hahn *et al.*, 1987). Other commonly used indices such as the Temperature Humidity Index (THI) and the hours THI exceeded 85 °C were not evaluated. It is clear that due to the low relative humidity during the Greek summertime they are



Fig. 1 – Comparison of fogging strategies based on the cumulative heat-stress duration criterion.

Table 2 - Heat-stress indices and daily water evaporating per pig when no-cooling or evaporative pads are used

Month	No-cooling			Evaporative pads, 'E _{Pads} '		
	Duration, h	Intensity, °C h	Duration, h	Intensity, °Ch	Daily water evaporating per pig, l day ⁻¹	
Мау	162	356	186	134	0.05	
June	500	1793	490	525	0.12	
July	714	3014	666	891	0.19	
August	646	2635	594	526	0.18	
September	345	1035	363	228	0.09	
Total	2367	8833	2299	2304		

not the most appropriate for determining pig apparent heatstress (Axaopoulos *et al.*, 1992).

Panagakis et al. (1991) defined the duration of heat-stress as the number of hours inside dry-bulb temperature exceeds the UCT, whereas the heat-stress intensity was defined using the following equation:

$$I = \int_{T} \int_{t} \Delta T \Delta t, \qquad (15)$$

where *I* is the heat-stress intensity in °C h, Δ T is the difference between the predicted inside dry-bulb temperature and the UCT in °C and Δ t is the time during which animals are housed under temperatures higher than the UCT in h.

3. Results and discussion

Simulation tests were initially run for the case of no-cooling and the case of evaporative pads, E_{Pads} the latter operating

when the inside dry-bulb temperature exceeded 26.1 °C and the relative humidity was not above 80%. The monthly values of the two heat-stress indices mentioned above and the water evaporating per pig daily (evaporative pads in operation) were calculated and are given in Table 2.

For each strategy, the values of the corresponding monthly heat-stress index were set equal to those calculated for ' E_{Pads} '. However, for strategy ' $F_{Duration}$ ' the indices of heat-stress duration and intensity during May were set equal to 162 h and 356 °C h, respectively and during September as equal to 345 h and 1035 °C h, respectively. These values do not match those calculated when evaporative pads are used, but do in the case of no-cooling because the latter are lower (Table 2).

A GLM factorial ANOVA (StatSoft, 2001) was calculated using fogging strategies ' $F_{Duration}$ ' and ' $F_{Intensity}$ ' and month (May–September) as the categorical predictors (independent factors) and each of the two heat-stress indices as the



Fig. 2 – Comparison of fogging strategies based on the cumulative heat-stress intensity criterion.



Fig. 3 – Comparison of fogging strategies based on monthly heat-stress duration.

Month	Strategy used			Difference between ${}^{\prime}F_{\rm Duration}{}^{\prime}$ and ${}^{\prime}F_{\rm Intensity}{}^{\prime}$		
	'F _{Duration} '		'F _{Intensity} '			
	Duration, h	Intensity, °Ch	Duration, h	Intensity, °Ch	Duration, %	Intensity, %
Мау	162 ^a	356 ^a	92	134	-43.2	-62.4
June	490	1727	270	525	-44.9	-69.6
July	666	2439	387	891	-41.9	-63.5
August	594	2319	328	526	-44.8	-77.3
September	345 ^a	1035 ^a	162	228	-53.0	-78.0
Total	2257	7876	1239	2304	-45.1	-70.7

'F_{Duration}': fogging with the necessary water evaporating so as to result in the same duration of heat-stress as when using evaporative pads. 'F_{Intensity}': fogging with the necessary water evaporating so as to result in the same intensity of heat-stress as when using evaporative pads. ^a Values are equal to those of no-cooling.

Table 3 – Heat-stress indices when strategies 'F_{Duration}' and 'F_{Intensity}' are used

dependent variable. For the whole 5-month period strategy ' $F_{Intensity}$ ' was significantly better than strategy ' $F_{Duration}$ ' in terms of heat-stress duration (P < 0.05; reduction 45.1%) and heat-stress intensity (P < 0.01; reduction 70.7%). Findings concerning cumulative duration and intensity of heat-stress are shown in Figs. 1 and 2, respectively. Furthermore, Table 3 shows that during each month strategy ' $F_{Intensity}$ ' resulted in a lower duration and intensity of heat-stress than strategy ' $F_{Duration}$ '. The statistical analysis showed no fogging strategy-month interaction. For both strategies and heat-stress indices July was the hottest (mean outside temperature equal



Fig. 4 – Comparison of fogging strategies based on monthly heat-stress intensity.

to $30.1 \,^{\circ}$ C) and most stressful month and May the coolest (mean outside temperature equal to $22.9 \,^{\circ}$ C) and the least stressful. Findings regarding strategy and month effect on the duration and intensity of heat-stress are shown in Figs. 3 and 4, respectively.

A close look at the hottest day (Fig. 5) shows that strategy ' $F_{Intensity}$ ' compared to strategy ' $F_{Duration}$ ' resulted in: (i) a lower daily average inside temperature (28.5 vs. 31.8 °C; reduction 10.4%), (ii) a smaller daily inside dry-bulb temperature variation (8.7 vs. 10.3 °C; reduction 15.5%) and (iii) a higher reduction of peak outside temperature (36.8 °C at 14:00 h), namely 2.9 vs. 0.2 °C, respectively. Contrast between strategy ' $F_{Duration}$ ' and strategy ' $F_{Intensity}$ ' reveals that when the former is used the temperature inside the building increases faster as the day becomes warmer and decreases slower after the peak temperature is reached. As a result during the warmer part of the day (i.e. 06:00–14:00 h) the temperature pattern of strategy

pig under different fogging strategies					
Daily water evaporating per pig under different fogging strategies, l day ⁻¹					
'F _{Duration} '	'F _{Intensity} '				
0.00 ^a	0.52				
0.09	2.19				
0.51	3.40				
0.37	4.63				
0.00 ^a	1.54				
0.19	2.46				
	Daily water evapor different fogging 'F _{Duration} ' 0.00 ^a 0.09 0.51 0.37 0.00 ^a 0.19				

Table 4 - Average amount of daily water evaporating per

^a Values are equal to those of no-cooling.



Fig. 5 - Effect of fogging strategy on inside dry-bulb temperature during the hottest day (Julian 176).

'F_{Duration}' follows that of the outside temperature more closely, whereas during the cooler part of the day (i.e. 00:00-06:00 h and 19:00-24:00 h) the temperature pattern of strategy 'F_{Intensity}' follows that of the outside temperature more closely. The above are due to the larger water quantity evaporating when strategy 'F_{Intensity}' is used and indicates that pigs are exposed to higher apparent heat-stress under strategy 'F_{Duration}'.

Comparison between strategies (Table 4) reveals that during the whole 5-month period and for strategy ' $F_{Duration}$ ' the average daily water evaporating per pig is only 7.7% of the water evaporating per pig when strategy ' $F_{Intensity}$ ' is used (' $F_{Duration}$ ': 0.191 day⁻¹ pig⁻¹ vs. ' $F_{Intensity}$ ': 2.461 day⁻¹ pig⁻¹). For areas characterised by high outside temperatures and scarce water resources this parameter could be of major importance. Use of evaporative pads, despite the disadvantage of a higher capital investment, appears to be the most appropriate in such cases.

4. Conclusions

Simulation comparison of fogging strategies in terms of heatstress duration and intensity under Greek summer conditions proved that strategy 'F_{Intensity}', namely fogging with the necessary water evaporating per pig so as to result to the same intensity of heat-stress as when using evaporative pads, 'E_{Pads}', was significantly better than strategy 'F_{Duration}', namely fogging with the necessary water evaporating per pig so as to result in the same duration of heat-stress as when using evaporative pads; 'E_{Pads}'. Strategy 'F_{Intensity}' resulted in lower daily average inside temperature, a smaller daily inside drybulb temperature variation and higher reduction of peak outside temperature. May was the least stressful month in terms of heat-stress duration and intensity, whereas July was the most stressful. For areas characterised by high outside temperatures and scarce water resources strategy 'F_{Intensity}' should be implemented with caution as larger quantities of water, in comparison to strategy 'F_{Duration}', need to evaporate. Future field experiments should be conducted to verify the above findings.

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