Mathematical modeling and optimization of CO as exhaust gas component of dual fuel CI engine coupled with biomass gasifier using diesel and mustard stalk

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Abstract

Punjab state is an agricultural state with twelve major crops has been sown round the year producing 14.53MT as crop residue. Huge quantity of crop residue poses a serious problem of stubble burning in the fields that leads to the burning of potential wealth and pollution across the state. Crop residue has a electricity generation potential of 1000MW annually[1], if properly utilized. In the present study a mathematical modeling and optimization of some experimental investigations of different combinations of diesel and producer gas with different input variables and output responses for dual fuel CI engine using mustard stalk has been presented. The input variables considered in the present study were type of fuel, equivalence ratio , load on engine and output responses were emission components (O_2, CO, CO_2, NO, NO_X, SO_2, FT, AT) , specific fuel consumption (SFC) and power output . Central composite design (CCD) of response surface methodology (RSM) using design of experiments (DOE) technique has been applied for the design of the experiments, developing models and optimization. The validity of developed models had been checked by analysis of variance (ANOVA) technique at 95% level of confidence. The comparison of experimental results with those predicted by models and optimization showed close proximity, which validates the models developed and optimization solutions obtained.

Keywords: *Dual fuel CI engines, producer gas, crop residue, mustard stalk, pollution, response surface methodology (RSM), central composite design (CCD), design of experiments (DOE), analysis of variance (ANOVA).*

1.0 Introduction

Punjab is an agricultural state with only 1.5 % of the geographical area of India, producing 22.5% wheat, 12% rice and 13% of cotton of the annual productions in India and producing a large amount of crop residue[1]. Crop residues in the mechanized farms in Punjab state are burned as this management has the lowest cost and minimum labour requirements[3]. Burning results in (the) loss of potential fuel, organic matter and nutrients of soil and increases pollution. The increase in pollution is evident from the fact that one tonne of straw burning releases 3kg of particulate matter, 60 kg of CO, 1460 kg of CO_2, 199 kg of ash and 2 kg of sulphur[4]. Burning of crop residue is easy and cheapest method being practiced globally, but burning of crop residue influenced the air quality and human health, so it should be used for energy production through different processes[5]. With the depletion of fossil fuels and present problem of stubble burning inspired the exploration of alternative renewable energy sources like producer gas derived from crop residue. At the present level of technology the gasifiers are more suited for heat applications than for shaft power applications[6]. The high contents of K+

and CL-1 in crop straw makes it difficult to burn[7]. Biomass quality can be improved by agricultural management[8]. Open core gasifier has been designed for the comparison of different biofuels[9]. The effect of equivalence ratio (ER) affects the gas composition from gasifier derived from wood and wood chips[10]. The the emission data varies with producer gas derived from wood pallets and wood briquettes in small combustor [11]. In dual fuel CI engine using rice husk, 31% of the diesel can be replaced with producer gas and emission parameters like CO, HC and smoke density were higher in dual mode[12]. Further using pigen pea stalks, corn cob and wood chips, the replacement of diesel in CI engine was 64%, 63% and 62% respectively [13]. The power out put of CI engine was almost comparable with diesel power with marginal higher efficiency and CO_2 emission was more at higher load condition [14]. CI engines operated on 60% biogas and 40% diesel performed better interms of brake thermal efficiency with minimum fuel consumption as compared to diesel[15]. The producer gas derived from sugarcane baggasse and carpentry waste reduced 51% diesel and 71% NOx emissions with slight reduction in power output[16]. Mathematical models were developed for dual fuel CI engine performance and emission for producer gas derived from rice husk using response surface methodology with design of experiments technique, were successfully Validated with ANOVA[17]. In all the referred work, little has been reported regarding the utilization of crop residue for power production using dual fuel CI engine coupled with gasifier. Further very little research work has been reported regarding the modeling and optimization of various input variables and output responses. In this work on of the crop residue (mustard stalk) is chosen as biomass gasifier feedstock. The effects of various input variables (load, ER, type of fuel) on output response CO using CCD of RSM using DOE has been studied and successfully developed mathematical models and optimized solutions. The models were validated using ANOVA and optimized solutions has been verified experimentally.

2.0 Materials and methods

2.1 Materials and experimental procedure

A mustard stalk and mustard stalk briquettes (crop residue) were used as the gasifier feed. The various properties of the mustard stalk has been given in Table 01 and Table 02. The diesel engine gasifier test rig was used for experimentation purpose. The detailed specifications of the gasifier test rig is given in Table 03. A downdraft gasifier was used to produce the producer gas using mustard stalk as the gasifier fuel. The gasifier is directly connected to CI engine, which is further connected to 5 kW generator system with a provision to put the variable load on generator. The load on the generator was varied with the help of electric heaters each of 1KW. The producer gas from the gasifier enters the CI engine through inlet manifold through control valve. The detailed diagram of the gasifier test rig is shown in Figure 01.

Table 01: Properties of mustard stalk (proximate analysis)

Biomass Name	Moisture %age	Ash %age	Volatile Matter %age	Gross Calorific Value (kcal/kg)
Mustard Stalks	6.88	6.65	68.93	3933

Table 02: Properties of mustard stalk (ultimate analysis)

Biomass Name	Nitrogen %age	Carbon %age	Sulphur %age	Hydrogen %age	Oxygen %age
Mustard Stalks	1.314	40.55	0.367	6.124	43.965

The gasifier was charged from the top with mustard stalk fuel in batch modes. Air enters the gasifier through two nozzles fitted at the circumference of the gasifier. The producer gas generated leaves the gasifier at the bottom. The producer gas is then supplied to the CI engine after its cleaning through series of filters. The load of generator and equivalence ratio (ER) of the gasifier along with type of engine fuel were varied for various output responses. The CO was measured with the help of exhaust gas analyzer.

Table 03: Specifications of gasifier test rig

Model:	AG
Gasifier type	Downdraft
Rated gas flow	15 Nm^3/hr
Average gas calorific value	1,000 $kcal/Nm^3$
Gasification temperature	1050-1100^oC
Fuel storage capacity	40 Kg
Ash storage and removal	Storage below the grate in the reactor & removal manual in the batch mode.
Start up	Through engine suction/blower.
Fuel type and size	Wood / woody waste with maximum dimension not exceeding 30 mm.
Permissible moisture in biomass	5 to 20% (wet basis).
Biomass charging	Batch mode, by topping up once every four hours.
Rated hourly consumption	4 to 5 Kg
Typical conversion efficiency:	Over 75%

Figure 01: Gasifier test rig

2.2 Design of experiments

The input design variables, output design responses and technique of experiments employed for the experiments has been described below;

2.2.1 Input design variables

The input design variables considered in the present work were load on engine, type of fuel and equivalence ratio (ER). The various experimental conditions are shown in Table 04. In the present work the effect of load on engine, type of fuel and ER has been studied on the exhaust of the engine in terms of CO concentration.

Table 04: Experimental conditions

Variables	Levels with range		
	Level 1	Level 2	Level 3
Type of fuel	Fuel I (Diesel)	Fuel II (Diesel + Mustard Stalks)	Fuel III (Diesel + Mustard Stalk Briquettes)
Load (kW)	1	3	5
ER	0.25	0.315	0.38

2.2.2 Response surface methodology (RSM)

Response surface methodology is a collection of mathematical and statistical techniques useful for analyzing problems having several independent variables which influence a dependent variables or response and goal is to optimize the response variable (*Montgomery D.C. (1984)*). In the most of the problems, relationship between response and independent variables is not known. The eventual objective of RSM is to determine the optimum operating conditions for the system, or to determine a region of the factor space in which the operating specifications are satisfied. Central composite design (CCD) gives over determined second order polynomial approximations. In other words, there are more design points in the design than there are undetermined coefficients in second order polynomial approximations. So CCD technique of RSM has been used in the design of experiments.

2.2.3 Design matrix

The various experiments with different combinations of design variables (Table 04) and output responses (Total 10) have been designed using design expert-10 software and the the detailed design summary is shown in Table 05. Total 39 experiments have been conducted as per the design matrix.

Table 05: Design Summary

		Fac 1	Fac 2	Fac 3	Res 1	Res 2	Res 3	Res 4	Res 5	Res 6	Res 7	Res 8	Res 9	Res 10
Std	Run	A: LOAD	B: ER	C: FUEL	SFC	POWER OUTPUT	O_2	CO	NO	CO_2	FT	NO_X	SO_2	AT
		Kw			ml/min-Kw	Kw	%AGE	ppm	ppm	%AGE	DEG. C	ppm	ppm	^0c
30	1	5	0.380	Fuel-III	4.0	5	16.00	2660	88.0	2.99	100.5	100.0	76.0	44.0
34	2	3	0.380	Fuel-III	4.0	3	17.00	2360	76.0	2.50	85.0	80.0	59.0	42.8
32	3	5	0.315	Fuel-III	2.5	5	17.00	2000	70.0	2.80	119.0	90.0	73.5	43.0
12	4	3	0.315	Fuel-I	6.0	3	21.50	1200	65.0	2.20	81.2	50.0	41.0	41.0
29	5	1	0.380	Fuel-III	8.0	1	18.00	1480	72.0	2.15	70.5	62.0	42.5	42.0
26	6	3	0.315	Fuel-II	4.0	3	20.00	1800	60.0	1.60	90.0	70.0	51.0	44.0
17	7	5	0.380	Fuel-II	5.0	5	17.60	2520	100.0	1.45	83.0	90.0	54.5	46.5
37	8	3	0.315	Fuel-III	2.8	3	17.29	1920	62.0	2.75	100.0	75.0	60.0	42.0
28	9	5	0.250	Fuel-III	4.0	5	18.50	1350	55.0	2.05	97.0	65.0	51.5	42.0
38	10	3	0.315	Fuel-III	2.6	3	18.00	1920	62.3	3.00	100.0	68.5	63.0	42.0
7	11	3	0.250	Fuel-I	6.0	3	21.50	1202	65.1	2.20	81.2	61.0	43.5	41.2
9	12	3	0.315	Fuel-I	5.5	3	21.50	1205	65.0	2.30	81.2	50.0	41.5	41.1
23	13	3	0.315	Fuel-II	4.5	3	20.00	1805	62.2	1.70	93.0	72.0	50.0	44.1
20	14	3	0.250	Fuel-II	5.3	3	20.87	1340	65.2	1.62	76.0	55.0	35.0	43.0

22	15	3	0.315	Fuel-II	4.0	3	20.00	1810	64.0	1.70	92.0	73.0	52.0	43.0
18	16	1	0.315	Fuel-II	7.0	1	21.05	1120	57.5	1.40	82.0	65.0	41.0	42.5
11	17	3	0.315	Fuel-I	6.0	3	21.50	1204	65.2	2.10	81.2	50.0	41.8	41.2
35	18	3	0.315	Fuel-III	2.6	3	17.88	1920	62.4	2.50	100.0	75.0	62.0	42.1
4	19	5	0.380	Fuel-I	5.6	5	20.00	1400	90.0	2.10	130.0	98.0	72.0	43.1
1	20	1	0.250	Fuel-I	12.0	1	23.00	1000	55.0	1.50	49.5	47.0	32.0	39.1
16	21	1	0.380	Fuel-II	7.0	1	19.07	1300	66.0	1.20	62.5	60.0	37.0	44.0
14	22	1	0.250	Fuel-II	9.5	1	23.00	870	62.0	1.60	68.0	45.0	26.0	42.5
13	23	3	0.315	Fuel-I	6.5	3	21.50	1201	65.3	2.10	82.0	50.0	41.9	41.3
10	24	3	0.315	Fuel-I	7.0	3	21.50	1205	65.0	2.30	82.0	50.0	41.2	41.2
2	25	5	0.250	Fuel-I	5.6	5	20.00	1410	90.1	2.10	130.0	98.0	72.0	43.1
15	26	5	0.250	Fuel-II	5.0	5	19.50	1290	80.0	1.70	90.0	68.5	43.5	44.0
27	27	1	0.250	Fuel-III	8.0	1	21.00	1130	34.0	1.50	67.5	46.0	32.0	40.0
24	28	3	0.315	Fuel-II	4.0	3	20.00	1825	60.3	1.60	90.0	70.0	50.5	44.1
3	29	1	0.380	Fuel-I	12.0	1	23.00	1010	55.1	1.50	49.5	47.0	32.0	39.1
8	30	3	0.380	Fuel-I	6.0	3	21.50	1205	65.0	2.20	81.2	61.0	43.5	41.2
6	31	5	0.315	Fuel-I	5.6	5	20.00	1412	90.0	2.00	130.0	96.0	71.5	43.3
19	32	5	0.315	Fuel-II	4.4	5	19.08	1950	82.0	1.62	102.1	86.0	58.0	45.5
25	33	3	0.315	Fuel-II	4.0	3	20.00	1820	60.2	1.60	90.0	70.0	53.0	44.0
33	34	3	0.250	Fuel-III	4.0	3	20.00	1510	45.0	1.75	80.0	53.0	41.5	40.1
5	35	1	0.315	D	12.0	1	23.00	1012	55.2	1.60	49.5	34.2	30.0	39.0
21	36	3	0.380	D+MS	3.3	3	18.00	2200	75.3	1.33	70.0	70.0	46.5	45.0
31	37	1	0.315	D+MSB	7.0	1	19.00	1280	55.0	2.04	90.0	63.0	47.0	41.0
39	38	3	0.315	D+MSB	2.5	3	18.00	1920	62.5	2.75	100.0	75.0	60.5	42.0
36	39	3	0.315	D+MSB	2.6	3	17.29	1920	62.3	2.90	100.0	75.0	61.0	42.1

2.3 Modeling response variables

For each response with given variables, the mathematical models had been developed using the software (Design Expert-10) for all the three modes of engine operation with various input variables and output responses (gaseous components of emission are discussed here). The ANOVA and Fishers statistical test (F test) were performed to check the adequacy of models as well as the significance of individual parameters. The various models were developed as follows in equations 1-21;

Fuel I

$$CO=804.07 + 104.04 \times LOAD + 5.88 \times ER$$

$$-0.38 \times LOAD \times ER+1.34 \times LOAD^2-738.62 \times ER^2 \qquad 1$$

Fuel II

$$CO=-972.09+135.26 \times LOAD+7964.90 \times ER$$

$$+1538.46 \times LOAD \times ER-69.00 \times LOAD^2-9712.30 \times ER^2 \qquad 2$$

Fuel III

$$CO=829.58 + 15.12 \times LOAD-1339.25 \times ER$$

$$+1846.15 \times LOAD \times ER-70.00 \times LOAD^2+3550.29 \times ER^2 \qquad 3$$

2.3.1 Model adequacy test for CO

Table 6: Analysis of variance for CO (ppm)

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value**	
Model	7.544E+006	17	4.438E+005	8498.41	< 0.0001	significant
A-LOAD	1.862E+006	1	1.862E+006	35667.67	< 0.0001	
B-ER	1.407E+006	1	1.407E+006	26950.79	< 0.0001	
C-FUEL	2.516E+006	2	1.258E+006	24090.48	< 0.0001	
AB	2.523E+005	1	2.523E+005	4831.78	< 0.0001	
AC	1.434E+005	2	71716.67	1373.44	< 0.0001	
BC	7.011E+005	2	3.506E+005	6713.70	< 0.0001	
A^2	2.792E+005	1	2.792E+005	5346.10	< 0.0001	
B^2	782.56	1	782.56	14.99	0.0009	
Residual	1096.55	21	52.22			
Lack of Fit	644.55	9	71.62	1.90	0.1485	not significant
Pure Error	452.00	12	37.67			
Cor Total	7.545E+006	38				

Std. Dev.	7.23	R-Squared	0.9999
Mean	1556.05	Adj R-Squared	0.9997
C.V. %	0.46	Pred R-Squared	0.9991
PRESS	7082.64	Adeq Precision	367.409

Stability of the model was validated using analysis of variance (ANOVA). The output showed that model was significant with p values less than 0.0001 as shown in Table 6 for CO concentration. The reference limit for p was chosen as 0.05 means, model is significant at 95% confidence level. Lack of fit is non significant further validates the model. The regression statics goodness of fit (R^2) (R^2 = model variability/ actual data variability) indicates the total variability of response after considering the significant factors. The R^2 value 0.9999 shows that model is fit in the experiments and model explain the experiments upto 99.99%, thus model is adequate to represent the process. R^2 adjusted value 0.9997 and R^2 predicted value 0.9991 are in sound agreement with each other for adequate model. MS value 443800 for the model is many times larger than MS value 52.22 for residual , thus high computed F value of the model ($F=MS_{Model}/MS_{Residual}$, where MS=SS/DF) implies that model is significant. Adequate precision (Signal/Noise) 367.407, is greater than 4, indicates that signal is adequate. Thus overall prediction capability of the model seems very satisfactory as per the criteria selected. Low value of CV 0.46% indicates the improved precision and reliability of the conducted experiments.

The lowest values of standard deviation 7.23 and PRESS (Predicted Error Sum of Squares) 7082.64 further validates the selection of the present model.

2.4 Optimization

Optimization is the combination of various factor levels that simultaneously satisfy the requirements as per the selected criteria for each of the responses and the variables. Using the optimization criteria, the various optimization solutions have been obtained as shown in Table 7.

Table 7: Optimization Solutions

NO	LOAD	ER	FUEL	SFC	POUT	O_2	CO	NO	CO_2	FT	NO_X	SO_2	AT	Dr
1	3.2	0.25	Fuel III	3.7	3.2	19.64	1525.50	45.09	1.90	81.08	54.13	42.97	40.64	0.662
2	3.2	0.25	Fuel III	3.7	3.2	19.64	1525.24	45.04	1.90	81.01	54.09	42.92	40.64	0.662
3	3.2	0.25	Fuel III	3.7	3.2	19.63	1525.90	45.16	1.90	81.19	54.21	43.04	40.65	0.662
4	3.1	0.25	Fuel III	3.7	3.1	19.65	1524.80	44.96	1.90	80.89	54.02	42.85	40.63	0.662
5	3.2	0.25	Fuel III	3.7	3.2	19.62	1526.28	45.24	1.90	81.32	54.29	43.12	40.66	0.662

* POUT= Power Output Dr=Desirability

3.0 Results and discussions

3.1 Comparison of CO concentration for various fuels

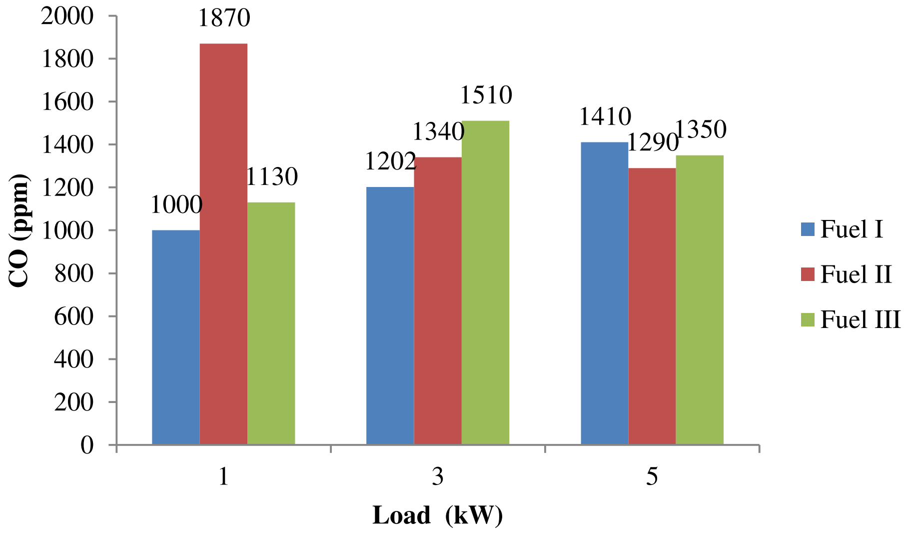

Figure 2: Variation of CO concentration with load at ER=0.25 for various fuels

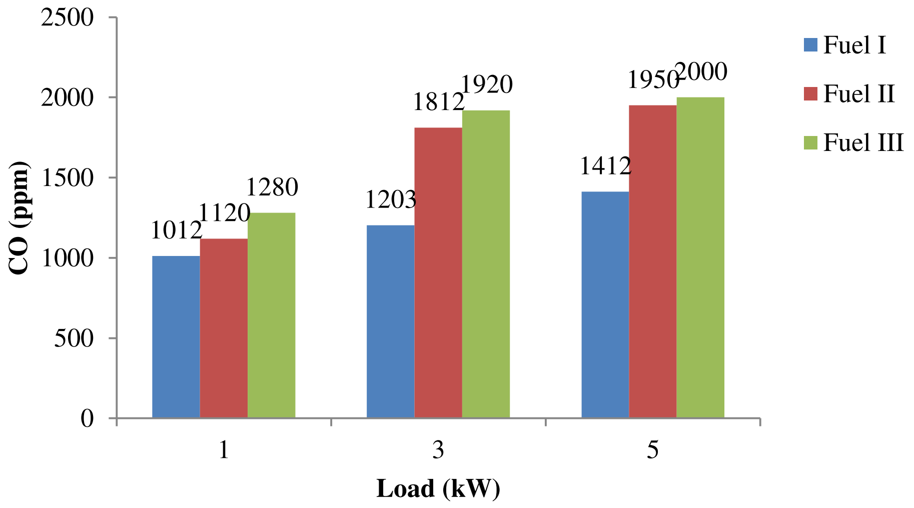

Figure 3: Variation of CO concentration with load at ER=0.315 for various fuels

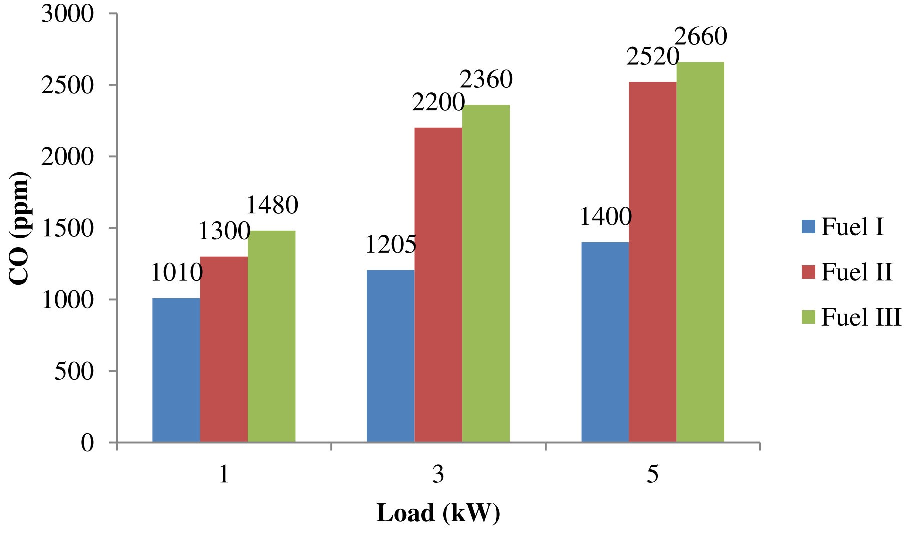

Figure 4: Variation of CO concentration with load at ER=0.38 for various fuels

The variation of CO concentration in exhaust gas at different values of load and ER for all the dual fuel operations with reference to diesel fuel has been given in Table 8.

Table 8: Recommendation of gasifier fuels at different values of ER and load

ER	Load (kW)	Fuel Recommended	Maximum “Down” and Minimum “Up” (CO %age)
0.25	1	Fuel III	13 (up)
	3	Fuel II	11 (up)
	5	Fuel II	9 (down)
0.315	1	Fuel II	12 (up)
	3	Fuel II	51 (up)

	5	Fuel II	38 (up)
0.38	1	Fuel II	29 (up)
	3	Fuel II	83 (up)
	5	Fuel II	80 (up)

4.0 Conclusions

1. Fixed carbon, sulphur, moisture contents, Nitrogen contents in mustard stalk is almost same as in coal, where as Hydrogen, oxygen, volatile matter and calorific values of mustard stalk are more as compared to coal and ash content is less as compared to coal.
2. The successful models have been developed for all the responses and effects of variables on the responses in all the three modes of operations have been correlated with the performance phenomenon. The effects of various performance parameters on CO are as follows;

i) In all the three modes of operations, concentration of CO increases with increase in load on the engine.ER has no effect in diesel mode but in dual modes increase in ER further increases the concentration of CO.

ii) In dual fuel mode operations, recommendations for maximum decrease (↓) or minimum increase (↑) of CO %age in exhaust gas as compared to diesel mode.

- At 1kW load: fuel II, ER=0.315, 12% (↑)
- At 3 kW load: fuel II, ER=0.25, 11% (↑)
- At 5 kW load: fuel II, ER=0.25, 9% (↓)

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